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Fibrous Microplastics as an Independent Risk Factor: Bioaccumulation, Gut–Liver Translocation, and Trophic Biomagnification in Marine Food WebsMarine Trophic Chains

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Abstract:

Fibrous microplastics dominate marine debris yet remain understudied compared with spherical and fragmented forms. Their high aspect ratio (10–50) confers unique mechanical flexibility and surface reactivity. In controlled exposure experiments (10–1,000 μg L^{-1}; 7–60 days), fish and bivalves retained fibers in intestinal villi with a bioaccumulation factor of 3.8 ± 0.4, three to four times higher than other morphologies. Micro-FTIR imaging tracked fibers crossing the intestinal epithelium and localizing in hepatic lobules, indicating a novel "gut–liver" pathway. At environmentally relevant concentrations (10 μg L^{-1}, 60 days), fibers disrupted eight energy metabolism pathways, doubled superoxide dismutase activity, and tripled tumor necrosis factor-α expression, suggesting chronic metabolic and inflammatory stress. In a three-level food web experiment (algae → shrimp → fish), fibers exhibited significant biomagnification (BMF = 1.75 ± 0.12), unlike spheres or fragments (BMF < 1.0). These findings demonstrate that morphology is an independent determinant of microplastic risk, beyond size and concentration.

Keywords: fibrous microplastics; bioaccumulation; gut–liver pathway; chronic toxicity; morphology-toxicity model; energy metabolism

1. Introduction

Microplastic pollution has emerged as a pressing global environmental issue, receiving growing attention in recent decades due to its persistence, ubiquity, and ecological consequences. Plastics, owing to their durability, low cost, and versatility, have become indispensable in modern society, yet their massive

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production and inadequate disposal practices have led to widespread contamination of marine environments. Large plastic debris gradually degrades through physical, chemical, and biological processes, producing particles less than five millimeters in size that are collectively known as microplastics. These particles disperse across a wide range of aquatic habitats, from surface waters to deep-sea sediments, and interact intensively with biological communities. Their small size and surface reactivity facilitate ingestion by organisms, thereby integrating them into food webs and introducing a novel dimension of anthropogenic stress to marine ecosystems.

The ecological risks posed by microplastics have been well documented. They are readily ingested by diverse organisms, ranging from plankton and filter feeders to commercially important fish and top predators. Once internalized, microplastics can cause physical blockage of digestive tracts, abrasion of epithelial tissues, and reduced nutrient absorption. Beyond such mechanical effects, they can also serve as carriers for chemical additives, heavy metals, and persistent pollutants adsorbed from surrounding waters. In turn, these contaminants may leach into tissues, inducing oxidative stress, inflammation, and reproductive or developmental disruptions. Such processes can alter growth trajectories, impair survival, and weaken resilience at the individual level, while at broader scales they have the potential to destabilize community structures and reduce ecosystem functionality.

Despite increasing research efforts, significant knowledge gaps remain. A disproportionate focus has been placed on spherical microplastics, largely because they are commercially available and easy to manipulate in laboratory studies. In contrast, fibrous particles—derived from textiles, fishing gear, and degraded ropes—constitute the most abundant form of microplastics in marine environments, yet their ecological implications are comparatively underexplored. Fibers possess distinct characteristics, such as elongation, flexibility, and high surface area, which influence their transport, retention, and interaction with biota. These features may allow them to entangle with plankton, penetrate tissues more effectively, or persist longer within digestive systems than spherical particles. However, systematic evaluations of these morphology-dependent effects are still lacking, leaving risk assessments incomplete and potentially biased.

The complexity of fibrous microplastic pollution extends beyond individual exposure. In natural ecosystems, these particles interact with sediments, biofilms, and microbial communities, influencing their fate and ecological behavior. Fibers can accumulate in benthic habitats, be resuspended by hydrodynamic forces, or act as substrates for microbial colonization, thereby modifying local biogeochemical cycles. When incorporated into food chains, their potential for trophic transfer and long-term accumulation raises questions about biomagnification, metabolic disruption, and the alteration of energy flows. Laboratory studies often rely on artificially high concentrations of particles, but the consequences of chronic, low-level exposure—more representative of real environments—are poorly understood. Such uncertainties hinder our ability to predict ecological outcomes under realistic scenarios.

The broader implications of this issue highlight its urgency. Microplastic pollution is not merely an ecological concern but also a matter of global governance and sustainable development. International environmental agreements and regional conservation initiatives increasingly recognize the need for robust scientific evidence to inform management actions. Fibrous microplastics, given their prevalence and persistence, pose risks that extend into the socio-economic domain, particularly through their potential influence on fisheries, seafood safety, and human health. Communities that rely heavily on marine resources may face both ecological and economic challenges if the impacts of fibrous particles are overlooked. Addressing these concerns requires a shift from general assessments of microplastics to more refined analyses that explicitly account for particle morphology.

The present study seeks to contribute to this refinement by employing controlled exposure experiments and food chain simulations to investigate the enrichment, migration, and metabolic consequences of fibrous microplastics in marine organisms. By systematically comparing morphology-driven differences in bioaccumulation and trophic transfer, this research provides new perspectives on how particle structure shapes ecological risks. The results are expected to advance understanding of microplastic pollution beyond generic categories, offering insights for the integration of morphology-specific considerations into ecological risk assessment frameworks. Ultimately, these findings aim to support biodiversity conservation, promote sustainable fisheries management, and strengthen the scientific basis for policy measures designed to safeguard marine ecosystems in an era of escalating anthropogenic pressures [1-2].

2. Literature review

Over the past decade, research on the accumulation of microplastics in marine organisms has expanded rapidly, but the available data remain highly fragmented. More than 70% of existing studies have relied on short-term (≤ 7 days) high-concentration exposures at levels of 1–100 mg L^{-1}, while only a few extended experiments (n = 4) investigated environmentally relevant concentrations of

1–100 μg L^{-1} for durations of 30 days or longer. In terms of particle morphology, the majority of toxicological assessments have focused on spherical particles (68%), whereas fibrous particles—the most abundant form in marine environments—accounted for only 11%. Among these limited fiber-related studies, only two systematically compared differences in aspect ratio (AR 2–50). Species selection has also been narrow: zebrafish, mussels, and marine killifish represent 81% of model organisms used, while high-trophic-level economic fish (e.g., Sparidae, Salmonidae) and benthic filter feeders (e.g., oysters) have received insufficient attention [3-5]. Detection endpoints have typically emphasized total tissue burdens, with some reports of cross-organ transfer into the liver and muscle, yet these were almost exclusively conducted with spherical particles. As a result, fibrous microplastics remain conspicuously absent from experimental design frameworks. Furthermore, the concentration–time windows commonly adopted in laboratory experiments are severely mismatched with real marine environments, where exposure typically occurs at μg L^{-1} levels over months or years. This mismatch has prevented the establishment of chronic thresholds and created significant uncertainty in extrapolating laboratory findings to ecological risks. In summary, although the toxicological framework for spherical microplastics has become increasingly established, fibrous microplastics remain a "data desert," particularly regarding their long-term effects under environmentally relevant concentrations and the role of morphology as an independent determinant of toxicity.

3. Research Methods

A controlled three-factor experimental design was adopted, incorporating particle morphology (fibers, fragments, microspheres), concentration (10–1,000 μg L^{-1}), and exposure duration (7–60 days). To further evaluate morphology-dependent effects, a fiber length-to-diameter ratio gradient (1:1–50:1) was introduced, enabling the analysis of shape-related parameters. Trophic transfer and amplification were assessed using a three-level microcosm system consisting of algae, crustaceans, and fish, with ^{13}C stable isotope tracing applied to quantify both bioaccumulation and biomagnification coefficients [6-8].

4. Results

The experiments demonstrated that fibrous microplastics exhibit distinct accumulation and toxicity patterns compared with spherical and fragmented forms. Across multiple endpoints—including intestinal retention, tissue migration, metabolic disruption, and trophic transfer—fibers consistently showed higher biological impact, supporting morphology as a key determinant of microplastic risk.

Fibrous particles displayed significantly greater intestinal retention than other morphologies (BCF = 3.8 ± 0.4, $p < 0.01$). Micro-FTIR imaging provided direct evidence of fiber penetration through the intestinal epithelium and localization in hepatic lobules. Chronic exposure (10 μg L^{-1} for 60 days) induced substantial metabolic disturbances, with eight differential metabolites identified in liver profiles (VIP > 1.5, $p < 0.05$). Antioxidant and inflammatory responses were also observed: superoxide dismutase (SOD) activity increased 2.5-fold and tumor necrosis factor-α (TNF-α) expression was upregulated 3.5-fold (both $p < 0.01$). In food chain simulations, fibrous microplastics exhibited significant biomagnification (BMF = 1.75 ± 0.12, $p < 0.01$), whereas spheres and fragments showed values below unity.

Based on these findings, a quantitative "form-to-toxicity" model ($r^2 = 0.84$, $p < 0.001$) was established, capable of predicting ecological risks associated with fibrous microplastics of different aspect ratios [12]. This model highlights morphology as an independent predictor of toxicity, providing a new framework for integrating particle shape into ecological risk assessments [9-12].

5. Conclusion

Fibrous microplastics with a length-to-width ratio of ≥ 10 show markedly higher bioaccumulation in marine organisms compared with spherical and fragmented particles. Their bioaccumulation coefficient reached 3.8 ± 0.4, and microstructural analysis confirmed their ability to penetrate intestinal epithelia and deposit in hepatic lobules. Chronic exposure at an environmentally relevant concentration of 10 μg L^{-1} for 60 days disrupted eight energy metabolism pathways, increased superoxide dismutase (SOD) activity by 2.5 times, and upregulated tumor necrosis factor-α (TNF-α) expression by 3.5 times, indicating significant metabolic and inflammatory stress. Food chain experiments further demonstrated that fibers undergo notable biomagnification (BMF = 1.75), whereas spheres and fragments remained below unity. These findings differ from earlier high-dose acute studies focused mainly on spherical particles, showing that under realistic environmental conditions, morphology alone can determine cross-organ migration and chronic toxicity, thereby establishing aspect ratio as an independent determinant of ecological risk. Incorporating morphology into ecological risk assessments can strengthen global water quality standards, guide targeted source-control strategies for fibrous plastics, and enhance protection of both fisheries and human health. Nevertheless, the present experiments

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were conducted under simplified semi-static conditions and limited to fish and crustaceans, which restrict extrapolation to higher trophic organisms and marine mammals. Future studies should therefore emphasize in situ estuary–nearshore exposure systems to examine the influence of hydrodynamics, organic matter, and co-pollutants on fiber bioavailability, while coupling isotope tracing with field-scale mitigation projects such as degradable fishing gear recycling to evaluate ecological benefits under realistic marine conditions.

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