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UNRAVELING THE ENVIRONMENTAL FOOTPRINT OF PLASTICS AND CHEMICALS ON MARINE FOOD NETWORKS

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Abstract

The increasing accumulation of plastics and chemical pollutants in marine ecosystems has become a critical environmental concern, threatening biodiversity, food web stability, and human health. Plastics, particularly microplastics and nanoplastics, not only persist in the environment but also act as vectors for toxic chemical compounds such as persistent organic pollutants (POPs), heavy metals, and per- and polyfluoroalkyl substances (PFAS). This study aims to unravel the combined environmental footprint of plastics and associated chemicals on marine food networks by synthesizing findings from recent empirical and modeling studies. A systematic literature review (SLR) was conducted using Scopus, ScienceDirect, SpringerLink, and MDPI databases, covering publications from 2015 to 2025. Forty-two peer-reviewed articles were selected based on PRISMA 2020 guidelines, focusing on topics related to microplastic contamination, chemical pollutant interactions, bioaccumulation, and trophic transfer. Data were analyzed through descriptive and thematic analysis, identifying key pathways, ecological impacts, and knowledge gaps. Findings reveal that microplastics facilitate the adsorption and transport of chemical pollutants through ingestion and trophic transfer, leading to bioaccumulation and, in some cases, biomagnification across trophic levels. Combined exposure induces oxidative stress, endocrine disruption, growth inhibition, and reproductive failure in marine organisms. These synergistic effects disrupt food web dynamics, reduce biomass, and pose emerging risks to seafood safety and human health. The review also identifies critical knowledge gaps in multipollutant interactions, long-term field studies, and integrated modeling approaches. This study emphasizes the need for multidisciplinary research, evidence-based policies, and integrated management strategies to mitigate the dual threats of plastic and chemical pollution. Strengthening global collaboration, enforcing stricter regulations on plastic additives, improving waste management systems, and promoting ocean monitoring programs are essential for safeguarding marine ecosystems and achieving Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water) and SDG 3 (Good Health and Well-being).

Keywords: microplastics, chemical pollutants, marine food web, bioaccumulation, biomagnification, ecotoxicology, sustainability

Introduction

In this modern era, the use of plastic has permeated almost all aspects of human life due to its lightweight, inexpensive, and durable nature. However, these durable properties are actually lacking when plastic ends up in the environment, especially marine ecosystems. Plastics that are dumped into the sea will undergo a process of fragmentation into microplastics and nano, and can function as a vector for harmful chemicals that are adsorbed or released from the plastic matrix. (Tuuri, 2023).

The presence of microplastics in the marine environment has been identified as one of the major threats to marine life since they can be ingested by organisms of the most basic trophic levels, such as plankton, and then move to higher predators through trophic transfer. (Tuuri, 2023) In fact, microplastics have the potential to disrupt the physiology of marine organisms through mechanisms such as inflammation, changes in gene expression, and growth inhibition (Tuuri, 2023).

In addition, plastics contain or attract a variety of toxic chemical compounds—such as plastic additives (e.g., phthalates, bisphenols), heavy metals, and persistent organic pollutants (POPs)—that can be released into seawater or stick to plastic surfaces. (Gallo et al., 2018) This process of interaction between microplastics and chemical compounds adds to the complexity of environmental impacts, as plastics can be vectors that facilitate the spread and bioaccumulation of toxic chemicals. (Guerrini, Mari, & Casagrandi, 2021).

The combination of physical aspects (fragmentation, absorption, displacement) and chemical (emission, adsorption) aspects makes the impact of plastics on seafood interweaving very complex. In other words, the environmental footprint of plastics and related chemicals is not only limited to the presence of particles—but also how they affect energy transfer, biomass, and the balance of marine ecosystems. (Vergara et al., 2025) Research on these interactions is important so that we can understand the extent of the synergistic or antagonistic effects between plastics and chemicals in the webbing of seafood.

In this context, the study *Unraveling the Environmental Footprint of Plastics and Chemicals on Marine Food Networks* aims to outline the relative contribution of plastics and chemicals to changes in the structure and function of seafood webs. Some of the focus points carried out include (1) the entry routes of plastics and chemicals into the seafood web, (2) the mechanisms of bioaccumulation and biomagnification, (3) the physiological and ecological impacts on marine organisms, and (4) the implications for food security and human health.

Building on previous studies that have shown that plastic and chemical pollution threaten marine ecosystems and health through trophic transfer (Shealy, 2025), this study is expected to present a deeper and more comprehensive understanding of the combined impacts (plastics + chemicals) in seafood webs. The findings of this study are expected to provide recommendations for policies for plastic management, chemical mitigation, and marine ecosystem conservation holistically.

Literature Review

Global Trends of Marine Pollution

In recent decades, the volume of plastic entering the ocean has increased significantly due to mass consumption and ineffective waste management systems. Each year, more than 8 million tons of plastic are estimated to end up in the ocean, creating a threat to marine ecosystems through fragmentation into microplastics and nanoplastics (Habumugisha et al., 2024). These plastics are not only persistent but also serve as vectors for various toxic chemicals such as heavy metals, pesticides, and persistent organic compounds (Amelia et al., 2021).

Microplastics as Chemical Carriers

Microplastics have a high surface area and hydrophobic properties that allow the adsorption of organic and inorganic compounds from the surrounding environment. This makes microplastics a secondary pollutant carrier medium that can be widely distributed through ocean currents (Menéndez-Pedriza & Jaumot, 2020). Studies by Weis and Alava (2023) show that interactions between microplastics and chemical pollutants can exacerbate cumulative toxicity through synergistic effects, increasing the risk of bioaccumulation in marine organisms.

Bioaccumulation and Biomagnification in Marine Food Webs

Plastic and chemical pollutants enter the seafood chain primarily through phytoplankton, zooplankton, and bivalves, then move to higher trophic levels such as predatory fish and marine mammals (Cverenkárová et al., 2021). An ecosystem modeling study in the Galápagos Islands by McMullen et al. (2024) shows the potential for microplastic biomagnification in key species such as penguins, which shows an increase in accumulation as trophic levels increase. This phenomenon raises concerns about human food safety through seafood consumption.

Combined Toxicological Effects

The combined toxic impact between microplastics and chemicals has been observed in various laboratory studies. For example, Soltanighias et al. (2024) reported that concomitant exposure between perfluoroalkyl substances (PFAS) and microplastics increases *Daphnia magna mortality* and interferes with reproductive function. Meanwhile, Yang et al. (2024) found a growth inhibition effect on marine algae due to complex interactions between microplastics and pharmaceutical products in the aquatic environment.

Knowledge Gaps and Emerging Perspectives

Although many studies have focused on the impacts of microplastics or chemicals separately, studies integrating the two in the context of seafood nets are still limited. Key challenges include the lack of field data on multipollutant bioaccumulation pathways, as well as the lack of predictive models that take into account synergistic and antagonistic effects in marine systems (Bastante-Rabadán et al., 2024). Therefore, a multidisciplinary approach that combines toxicology, trophic ecology, and systemic modeling is needed to comprehensively understand the combined impact.

Policy Implications and Future Research

Empirical findings confirm the need for evidence-based policies to reduce the environmental footprint of plastics and chemical pollutants, including regulation of plastic additives, improvement of recycling systems, and oversight of seafood supply chains (Covernton et al., 2022). Future research is suggested to assess chronic exposure under natural conditions, evaluate multipollutant trophic transfer, and develop a One Health framework that links the health of marine and human ecosystems.

Research Methods

Research Design

This study uses a systematic literature review (SLR) approach to identify, evaluate, and synthesize the latest scientific findings related to the combined impact of plastic and chemical pollution on *marine food networks*. This approach was chosen because it allows researchers to gain a comprehensive understanding of various empirical and experimental studies that address the interactions between microplastics, chemical contaminants, and marine organisms across trophic levels (Habumugisha et al., 2024; Cverenkárová et al., 2021).

Sources and Databases

Secondary data was collected from international indexed journals Scopus, ScienceDirect, SpringerLink, and MDPI, with a publication range between 2015–2025. The focus of the search was directed to articles with the themes: "microplastics and chemical pollutants," "marine food web/food chain," "bioaccumulation and biomagnification," and "combined toxicity in aquatic ecosystems." Keywords were combined using Boolean operators such as: ("microplastics" OR "nanoplastics") AND ("chemical pollutants" OR "toxic compounds") AND ("marine ecosystem" OR "food web" OR "trophic transfer") Only full-text, peer-reviewed, and English-language articles were included in the analysis.

Inclusion and Exclusion Criteria

To maintain the relevance and quality of the data, a selection was made based on the following criteria:

Inclusion:

1. Empirical studies or reviews that discuss the effects of plastics and chemicals on marine organisms.
2. Research that contains data on bioaccumulation, biomagnification, or toxic effects on seafood webs.
3. Articles that use laboratory methods, ecosystem models, or numerical simulations.

Exclusion:

4. Popular articles, opinions, or *policy briefs* without empirical data.
5. Irrelevant land-based (terrestrial) or freshwater studies.
6. Duplicate articles or do not meet methodological standards.

The selection process is carried out through three stages: identification, screening, and eligibility, referring to the PRISMA 2020 guidelines.

Data Analysis Procedure

The analysis is carried out through two approaches: Descriptive Analysis: grouping articles by year of publication, area of study, type of organism studied, and type of pollutant (plastic/chemical). Thematic Analysis: identifying key patterns such as:

1. Plastics and chemical entry routes into the food chain.
2. Mechanism of bioaccumulation & biomagnification.
3. Physiological and ecological impacts.
4. Synermatic/antagonistic effects.
5. Implications for human health.

This approach was adapted from the thematic synthesis method by Thomas & Harden (2008) and used to find key themes across studies.

Validity and Reliability

To increase validity, source triangulation was carried out through inter-database comparison, as well as peer checking on the results of thematic coding. Meanwhile, reliability is maintained by compiling documented search protocols and using assistive software such as Zotero for reference management and NVivo for thematic analysis.

Research Limitations

This research is desk-based and depends on the availability of published literature. Therefore, the results are limited to the context reported by previous studies and do not yet include dynamic actual field conditions. In addition, the heterogeneity of the study design and the variability of measurement parameters can give rise to interpretation bias.

Results and Discussion

Characteristics of the Studies Analyzed

From the selection process using the PRISMA 2020 guide, as many as 42 scientific articles were selected from the 2015–2025 time frame. The studies were mostly from Europe (35%), East and Southeast Asia (30%), and North America (20%), with a primary focus on coastal marine ecosystems and estuaries. As many as 60% of the research is experimental in the laboratory, 25% is field-based, and the remaining 15% is modelling studies (e.g. *Ecopath with Ecosim*). The majority of studies (≈70%) focused on microplastics (1 µm – 5 mm), while 20% on nanoplastics, and 10% discussed the interaction of chemical pollutants such as PAHs (Polycyclic Aromatic Hydrocarbons), PCBs (Polychlorinated Biphenyls), PFAS, and heavy metals. The types of organisms that are most often objected to include zooplankton, bivalves, small fish, and apex predators (McMullen et al., 2024; Cverenkárová et al., 2021).

Exposure and Bioaccumulation Pathways

Results from the literature show that the main routes of exposure to plastics and chemicals are through direct ingestion, adsorption on body surfaces, and the food chain. Microplastics that contain or carry chemical compounds can be easily ingested by phytoplankton and zooplankton, then move on to small fish and high trophic organisms such as seabirds and marine mammals (Habumugisha et al., 2024). Studies by Amelia et al. (2021) and Weis & Alava (2023) show that microplastic particles can accumulate toxic chemicals through the process of adsorption, thereby increasing the total concentration of pollutants in the organisms that ingest them. This effect is exacerbated by the hydrophobic properties of plastics, which strengthen the bonding ability with chemical compounds such as PCBs and DDT. The process of bioaccumulation is detected at various trophic levels, and in some cases biomagnification occurs, where concentrations of pollutants increase in apex predators. For example, *the Ecopath with Ecotracer* model shows a significant increase in microplastic levels in penguins in the Galápagos Islands (McMullen et al., 2024).

Physiological and Ecological Effects

The physiological effects of combined exposure to plastics and chemicals include oxidative stress, DNA damage, endocrine disorders, and decreased reproductive ability. In experiments on *Daphnia magna*, the combination of PFAS and microplastics increased mortality and lowered birth rates (Soltanighias et al., 2024). In addition to direct effects on individuals, studies also report ecological disturbances such as: decreased zooplankton biomass, changes in plankton community structure, reduced energy availability for higher trophic levels, which indicate an imbalance of the seafood web (Yang et al., 2024).

The synergistic (combined) effects between plastics and chemicals tend to be more severe than the single effects of each pollutant (Bastante-Rabadán et al., 2024), suggesting that the analysis should consider complex interactions between pollutants, rather than a single-contaminant approach.

The Role of Microplastics as Chemical Vectors

Thematic analysis confirms that microplastics play a role as transport vectors for chemical pollutants. This is reinforced by the findings of Menéndez-Pedriza & Jaumot (2020) which showed the ability of microplastics to absorb heavy metal compounds and persistent organic compounds, then release them in the digestive tract of marine organisms. Under certain environmental conditions—such as low pH or high temperatures—the release of chemicals from plastic surfaces increases, thereby magnifying the potential for toxicity (Habumugisha et al., 2024). This poses a risk not only to marine species, but also to humans through the consumption of contaminated seafood (Weis & Alava, 2023).

Implications for Food Health and Safety

From One Health's perspective, the presence of microplastics and chemical contaminants in seafood products for human consumption such as fish, shellfish, and shrimp poses a threat to food safety. The bioaccumulation of compounds such as BPAs, PAHs, and PFAS is known to disrupt the endocrine system and increase the risk of chronic diseases (Habumugisha et al., 2024).

Therefore, it is important for public policy and marine food industry oversight to develop safe limit standards against combined exposure to plastics and chemicals, as well as strengthen control of marine pollution at the source (Covernton et al., 2022).

Discussion and Synthesis

Findings from the literature show that the impact of plastic and chemical pollution on seafood nets is Complex and Multidimensional, involving physical-chemical-biological interactions, Tiered, as it affects from the basic trophic level to

the peak, Synermatic, where the combined pollutants produce greater effects, and Global, with variations in intensity based on location and human activity.
The joint study reinforces the urgency to develop a cross-sectoral mitigation strategy, including: reduction of single-use plastics, regulation of plastic additive chemicals, monitoring of bioindicators in marine ecosystems, and the application of ecosystem models for long-term impact prediction

Conclusion

Overall, the environmental footprint of plastics and chemicals in seafood nets is complex, synergistic, and extensive, creating serious threats to the sustainability of marine ecosystems and human health. Mitigation efforts must be carried out through the synergy of scientific research, environmental policy, and community participation to maintain marine food security and global ecosystem balance.

Recommendations for Policy and Government

***Plastics and Chemicals Regulation*:**

Governments need to strengthen regulations on single-use plastics, harmful additives (such as BPA, phthalates), and persistent chemical compounds (such as PCBs and PFAS) through production restrictions and waste treatment obligations. Integrated Monitoring System: Establish a national monitoring system to detect the presence of microplastics and chemicals in the ocean, sediments, and marine life. Use bioindicators such as shellfish, pelagic fish, or zooplankton. Improved Waste Management: Encourage the implementation of a circular economy with closed recycling systems, green industry incentives, and community-based waste management to prevent the entry of plastics into the ocean. Marine Food Safety Standards: It is necessary to establish safe limits for exposure to combined pollutants (microplastics + chemicals) in seafood, as well as safety certifications for fishery products exported and consumed domestically. Global Collaboration: Marine pollution is cross-border, so cooperation with international organizations such as UNEP, FAO, and IOC-UNESCO is needed for the harmonization of global standards and policies

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