



Review Article

Microplastics in Disposable Beverage Containers: A Systematic Review of Environmental and Human Health Risks

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Abstract

Background: The pervasive use of disposable beverage containers, particularly plastic-coated paper cups, has led to significant environmental and human health concerns due to the release of microplastics (MPs) and associated toxic chemicals. MPs, defined as plastic particles ranging from 1 μm to 5 mm, have been detected in various ecosystems and human food chains, posing risks such as metabolic disorders, endocrine disruption, and ecological damage. Despite their convenience, these containers contribute to global plastic pollution, with projections indicating a rise in plastic production to 600 million tons annually by 2050.

Aim: This systematic review aims to evaluate the environmental and human health risks posed by MPs leaching from disposable paper and plastic beverage containers. It also seeks to recommend mitigation strategies to address these risks.

Methods: A comprehensive literature search was conducted using databases such as PubMed, Scopus, Web of Science, and Google Scholar, focusing on peer-reviewed studies published between 2019 and 2025. Inclusion criteria encompassed studies on MPs' release, toxicity mechanisms, and environmental pathways. Data were extracted and synthesized thematically, covering chemical risk factors, environmental impacts, and health effects. Analytical methods included spectroscopy, microscopy, and toxicity assays using human cell lines and aquatic organisms.

Results: The review revealed that MPs and nanoplastics leach into beverages under thermal and mechanical stress, with studies detecting up to 25,000 particles per cup. These particles act as vectors for heavy metals and persistent organic pollutants, entering the food chain and causing bioaccumulation. Toxicological studies



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demonstrated cellular uptake, oxidative stress, and metabolic disruption in human cells at concentrations as low as 10–100 µg/mL. Environmental degradation of MPs contributes to climate change by releasing greenhouse gases

and disrupting carbon sequestration processes.

Conclusion: Disposable beverage containers are a significant source of MPs, with far-reaching implications for environmental and human health. Urgent measures are needed, including stricter regulations on plastic additives, the development of biodegradable alternatives, and public awareness campaigns to reduce single-use cup consumption. Future research should focus on standardizing MP detection methods and investigating long-term health impacts.

Introduction

The last 70 years have shown our society more dependent on plastics for their necessary daily lifestyle, with their use extent fairly gradually initially by 1.5 million tons of manufactured in 1950. After that, manufacturing enhanced rapidly from the establishment of the 21st century: most of all plastic always created has been industrial late 2000, then by 2017, yearly manufacturing extended 348 million tons, therefore. Looking at the prospect, plastic is predictable to improve even better reputation with a yearly manufacture of 600 million tons in 2050 (Karacsonyi, 2023). Reusable paper cups are widespread for overwhelming beverages which have an internal that is plastic-coated with a hydrophobic film prepared of habitually plastic (polyethylene) and occasionally of copolymers (Ranjan et al, 2021). Paperboard and paper are the greatest commonly used supplies in food packaging procedures. Their attractiveness stems from their preferred appearances, as they are inexpensive, easily obtainable, flexible, serve as a respectable barrier to oxygen, lightweight materials, microbial moisture and other entities. Reusable paper cups are the most frequently recycled as beverage bottles (Karacsonyi, 2023; Mohery et al., 2025). In modern life, plastics are one of the utmost suitable materials, permitting them to be extensively used in numerous fields. Many branches of the plastic industry through Microplastics (MPs) (plastic quantities in sizes between 1 µm - 5 mm) (Frias and Nash, 2019), particularly in chemistry, the food chain and materials science (Akbulut et al., 2024). Nevertheless, despite this advancement, there are daily unverifiable practices, which, unbeknownst to most, incline to environmental influences. For

example, are the massive pieces of single-use (disposable) paper cups used up and disposed. Disposable cups were familiarized in the second half of the last century to encourage the health of the public (substitute corrupt shared drinking cups near public drinking water services). Since then, they have permeated all sectors of society and particularly the cafes and coffee shops industry (Foteinis, 2020). However, their negative influences on human health cannot be ignored. Because of their non-biodegradable nature, they remain to gather in the environment, making tons of waste worldwide. Plastic is considered the greatest beneficial artificial ‘manmade’ material, made up of components taken from fossil fuel properties. It has prepared likely utmost of the technological and industrial revolutions between the 19th - 20th centuries. Hence, food and beverages are the possible route of Microplastics contact to individuals through the human food. Research verified a rough estimate of daily MPs ingested via beverages and food: male children of male adults of 142 particles, 113 particles, female adults of 126 particles, and female children of 106 particles, respectively. Annually, MPs ranging between 39,000-52,000 pieces are expended during Americans’ caloric consumption. Therefore, assumed the rising global apprehension over diet consumption, this subject has become an important consideration. Possible risks to individual health posed by MPs have garnered intense attention due to the extensive detection of MPs in the diet that is connected to humans (Jin et al., 2021). The influences disturbing the amount of MPs secreted from plastic packaging containers and materials into diets are the original MP concentration of the container structure, the

storing period of the diet in the plastic bottle and the heat to which the plastic material is exposed throughout its manufacture. The value of pH, hydrophobicity, and the presence of enzymes, surface properties and microbiota of a food, could likewise impact the relocation of MPs from the material contacted to the foodstuff matrix. Meanwhile, microplastics (MPs) bring potential risks to human health when plastics are consumed, and more requirements are needed for the incidence and abundance of human ingestion of MPs (Akbulut et al., 2024). This study focused on publications that concentrated on the health hazards of MP consumption from drinking sources, particularly environmental and chemical risks.

Objective of Research

The objective of this study is to review and analyze various reports and studies related to the health hazards of disposable paper and plastic food containers (environmental and chemical hazards), and to recommend measures to mitigate and reduce this risk.

Materials and Methods

Study Design

This systematic analytic review aimed to evaluate the health and environmental risks associated with microplastics (MPs) released from disposable paper cups, plastic bottles, and hot beverage consumption. The study synthesized findings from peer-reviewed articles, experimental studies, and environmental reports published between 2019 and 2025. The review adhered to PRISMA guidelines for systematic reviews where applicable, focusing on the identification, analysis, and integration of data related to MPs' toxicity, environmental persistence, and human exposure pathways.

Data Sources and Search Strategy

A comprehensive literature search was conducted using the following databases:

PubMed, Scopus, Web of Science, Google Scholar

Inclusion Criteria:

1. Studies published in English (2019–2025).
2. Primary research articles, meta-analyses, and reviews addressing MPs in beverage containers.
3. Studies quantifying MPs release, toxicity mechanisms, or environmental fate.

Exclusion Criteria:

1. Studies unrelated to human health or the environmental impacts of MPs.
2. Non-peer-reviewed articles or conference abstracts.

Data Extraction and Synthesis

Two independent reviewers extracted data using a standardized form, including:

- **Study characteristics** (author, year, country, sample size).
- **MPs detection methods** (e.g., microscopy, spectroscopy).
- **Key findings** (leaching rates, toxicological effects, environmental pathways).

Discrepancies were resolved through consensus or consultation with a third reviewer. Data were synthesized thematically:

1. Chemical Risk Factors: Additives (e.g., bisphenol A, phthalates) and heavy metals in cup linings.
2. Environmental Pathways: MPs' migration into aquatic/terrestrial ecosystems.
3. Health Impacts: Bioaccumulation, metabolic disruption, and toxicity in human cell lines (e.g., Caco-2, HT29).

Analytical Methods

1. MPs Quantification: Spectroscopy: FTIR and Raman spectroscopy identified polymer types (PE, PP, PS). Microscopy: SEM and TEM assessed particle size (1 μm –5 μm) and morphology. Mass Spectrometry: GC-MS detected leached chemicals (e.g., styrene, phthalates).

2. Toxicity Assays: In vitro models (human intestinal cells: Caco-2, HT29-MTX) exposed to MPs (0–100 µg/mL) for 24-72 h. Endpoints: cell viability (MTT assay), oxidative stress (ROS detection), barrier integrity (transepithelial resistance). In vivo studies: Aquatic organisms (Chironomus riparius, Nile tilapia) exposed to cup leachates; evaluated for growth inhibition, teratogenicity.
3. Environmental Simulation: Landfill conditions (pH 4.5–9, UV radiation, mechanical stress) to study MPs fragmentation. Leachate analysis for MPs and co-pollutants (heavy metals, PBDEs).

Quality Assessment

The Risk of Bias (RoB) tool for in vitro and in vivo studies was evaluated:

- a) Sample representativeness.
- b) Methodological rigour (controls, replication).
- c) Statistical validity.

Statistical Analysis

Descriptive statistics summarized MPs concentrations and leaching rates. Meta-regression (where feasible) explored dose-response

relationships. Software: R (v4.3.1) and GraphPad Prism (v9.0).

Ethical Considerations:

All cited studies adhered to ethical guidelines for animal/human research. No primary data involving humans or animals were collected.

Limitations: a) Heterogeneity in MPs detection protocols across studies. b) Limited long-term exposure data in humans.

Chemical risk factors on the human body

Numerous inorganic and organic additives are usually used to treat the cups. The reasons are to make them improve preferred goods like springiness, temperature stability, color, and resistance to infectious activities. It has been acknowledged that hypothetically toxic materials and their combinations occur in plastic resources (Mohery et al., 2024). Several studies in the past have revealed that harmful chemicals and substances may leach from paper and paperboard-based food packaging into the diet meant for people's consumption (Foteinis. 2020; Jin et al., 2021; Ranjan et al., 2021; Akbulut et al., 2021; Mohery et al., 2024; Kumar and Verma, 2025).

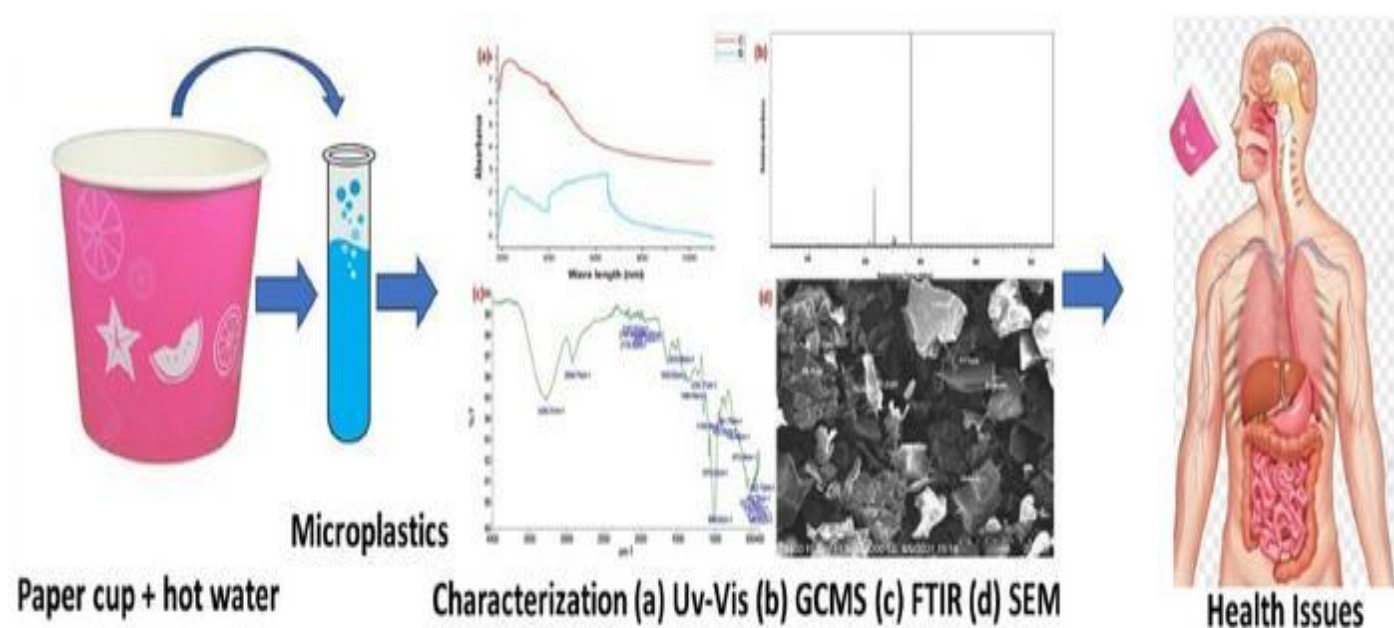


Figure 1: Graphical Health issues with microplastics from paper cup (Li, 2025)

Due to the nanosize of the plastic units, numerous organisms can easily ingest and accumulate in

various body parts, such as the liver, gills, testes, and blood, which may lead to metabolic disorders,

severe infections, and disturbances in numerous physical processes. Polystyrene nanoplastic (PNP) is extremely poisonous to creatures because of its capability to bio-accumulate in the tissues of the brain once transferred over the blood-brain barrier, which may limit the passageway of neurotoxins. Biomagnification due to additional concentrations of POPs at every tropic stage. Biologically, it might be deduced from organisms at a developed stage (persons, birds and fish) to lower-stage organisms (algae, zooplankton), which are due to particular variations in their digestion and attitudes. Nanoplastics are recognized to respond with other numerous chemical poisons structures (heavy metals, polycyclic aromatic hydrocarbons polymer monomers, such as bisphenol A, anti-ultraviolet radiation stabilizers, polybrominated diphenyl ethers, and phthalates), present in water which are ingested by water organisms that makes acute poisoning symptoms, endocrine illnesses, and reproduction toxicity (Singh et al, 2021).

The main metabolic body part that regulates the numerous metabolic pathways linking to different organs is the Liver, and it is the main detoxifying tissue in the human body [Rui, 2014]. It plays a major part in preserving the energy of the human body by regulating numerous passageways that participate in glucose digestion (Roseman et al., 2018). In the liver, glucose as glycogen is stored and is the single source of blood glucose. Besides, it brings glucose to various organs of the human body, which serve as the major sites for gluconeogenesis. Oxidation of proteins in the liver arranges for the greatest amount of energy essential for the liver. The protein absorption participates in the response of protein with aquatic organisms to the formula of amino acids and dipeptides (Haldar et al., 2023), where the amino acids are additionally digested into ammonia and keto acids. Therefore, urea

production is over and done with; the urea cycle proceeds individually in the human body's liver. This means the basic metabolism of toxic chemicals is in the liver (Wang et al., 2022).

Banaei et al. (2024) assessed the toxicity of leachate units from commercially obtainable tea bags by exposing three human intestinal cell lines (Caco-2, HT29, HT29-MTX) to iDye Poly-Pink-stained nanoplastics (NPLs). After 24 h at 100 µg/mL, significant approval of PP-NPLs was detected in the secretion of mucus by HT29-MTX cells, CL-NPLs in both HT29 and HT29-MTX cells, and NY6-NPLs chiefly in Caco-2 cells.

Environmental impact and health hazards of microplastics in tea

The negative consequence of microplastics in the different environmental matrices is a need of the day for sustainable management and persistence of a healthy environment. The ingestion of microplastics by different environmental matrices (air, water, soil, sediment, flora, fauna and ice) is raising alarm among the scientific community, managers, policy makers and the general public (Shen et al., 2025). These synthetic polymers are environmental pollutants themselves and act as paths of transport of co-contamination, but they are also imitated of the recent and contemporary period in the middle of the 20th century. Nowadays, microplastic pollution has been ubiquitously detected in the environments of marine water, freshwater, agroecosystems, atmosphere, food and drinking water, biota, and other remote locations. Moreover, a limited number of recent studies reported the accumulation of MPs in various environments (Senapathi and Sekar, 2023). The release of microplastics and other toxic substances from plastic-lined tea bags and paper cups poses human health and environmental risks (Fig. 2).

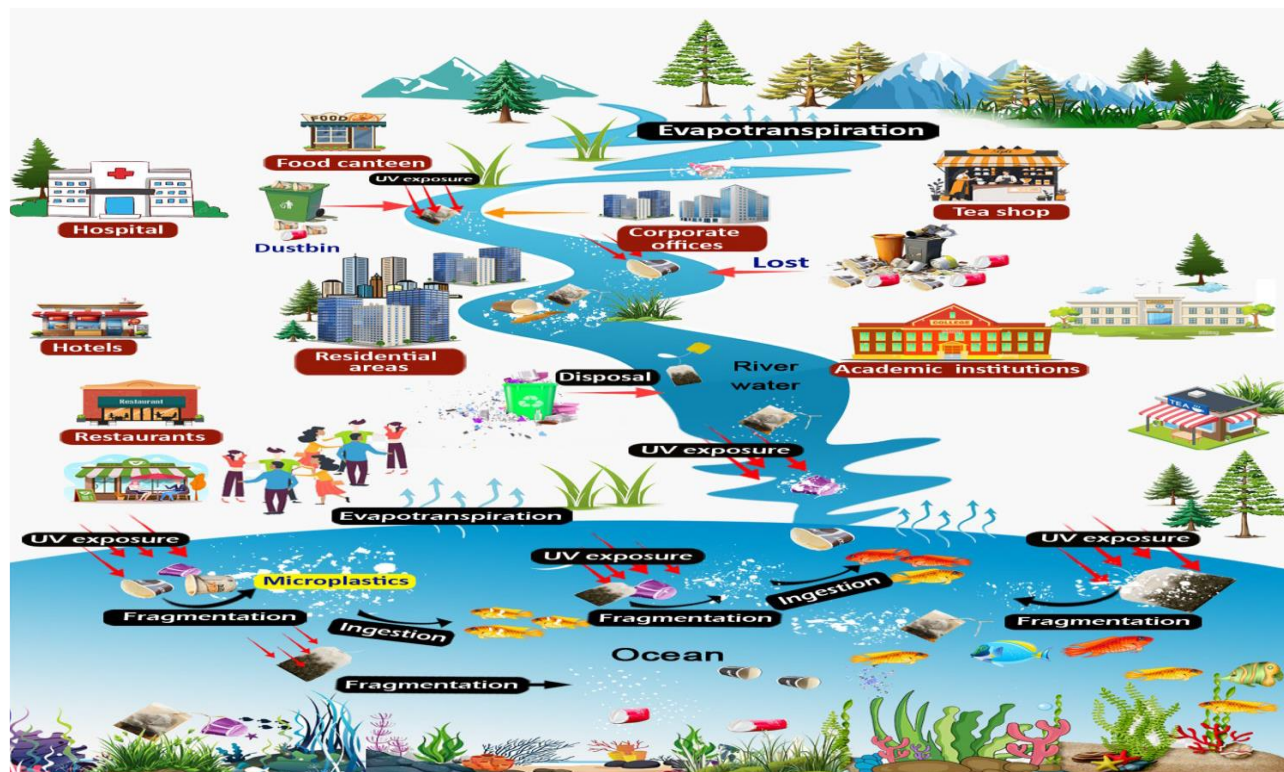


Fig. 2. Fate of microplastics in aquatic and terrestrial environments and their link to the food chain through surface runoff and littering (Kumar and Verma, 2025)

Usually used tea bags and paper cups, mainly composed of polymeric materials, often enter the surroundings through disposal in dumpsites, landfills, or littering in public spaces [Neha et al., 2024]. Paper cups and tea bags waste deposited in landfills are exposed to extreme environmental conditions. Environmental elements, like risky pH (ranging from 4.5 to 9), heat, physical stress, high salinity, UV radiation, fluctuating temperatures, and the 47-generation of gas (e.g., CH and CO₂) in landfills, affect the division of tea back and paper cups, plastics into minor microplastics. Furthermore, microbes increasing in landfill circumstances may simplify the biodegradation of plastic particles into nanoplastics or microplastics (Chamane et al., 2023). At landfill locations, leachate produced as precipitation infiltrates among waste locations is a substantial source of pollution, including ecological microplastics. This is because a large reduction is twofold. First, paper is diverted from landfills, and therefore, the equimolar combination of methane and Co₂, shaped from its anaerobic putrefaction in landfills, is not produced. Second, paper reutilizing due to reducing the usage of resources and energy, like

fossil fuels and deforestation for paper production. As such, paper cups have recycling value equivalent to their avoided environmental impact (Foteinis, 2020). Plastics are broken down into microplastics through thermo-oxidative and thermo-mechanical processes.

The long-term presence of microplastics in ecosystems plays a notable role in exacerbating global warming and climate change through various linked mechanisms. These include the release of greenhouse gases, interference with natural carbon storage processes, and harmful effects on ecological systems. Microplastics, mostly composed of durable polymers like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), break down gradually through processes such as exposure to light, heat, and physical wear. As microplastics degrade, they release significant amounts of greenhouse gases-primarily carbon dioxide (CO₂) and methane (CH₄) intensifying the greenhouse effect and increasing atmospheric GHG levels (Kumar and Verma, 2025)⁹. They also disrupt natural carbon storage mechanisms in both land and marine environments. In soil, microplastics

modify microbial communities and soil structure, weakening its ability to retain carbon. Research by Rillig et al. (2021) found that microplastics in farmland soils harm beneficial microbes involved in breaking down organic matter, which may reduce carbon absorption. Furthermore, microplastics transport harmful contaminants like persistent organic pollutants (POPs) and heavy metals, posing additional risks to ecosystems that regulate the climate. For example, toxic chemicals such as polybrominated diphenyl ethers (PBDEs), which attach to microplastic particles, can damage marine species critical to carbon cycling processes. Tumwesigye et al. (2023) highlighted that microplastics act as carriers for such contaminants, indirectly weakening vital ecosystem functions that help regulate carbon equilibrium. This chain of disturbances undermines crucial ecological processes needed to counteract climate change effects.

The environmental impact of foam cups persists long after disposal, primarily through two key pathways: landfill leachates and gas emissions. When landfills are sealed with a soil cover, microbial activity continues to generate heat, increasing waste temperatures. Under these conditions, styrene-a key component of foam cups, becomes chemically reactive, exacerbating the toxicity of already polluted leachate and raising treatment costs. Additionally, while organic waste decomposition produces usable biogas, the presence of foam cups diminishes this gas yield (Islam et al., 2024).

Foam cups are also vulnerable to photodegradation; prolonged exposure to sunlight breaks them down into fine particles that may degrade soil quality. Their lightweight nature further compounds their environmental harm, as wind easily scatters them from disposal sites, leading to urban litter and sewer blockages. When improperly discarded during outdoor activities, these cups often end up in waterways, threatening marine ecosystems (Ashraf, 2020).

The pervasive buildup of plastic waste is degrading ecosystems that form the foundation of key economic sectors. A particularly alarming

consequence is the infiltration of microplastics into food chains across marine and terrestrial environments, ultimately entering human diets, many plastics contain endocrine-disrupting compounds, and chronic exposure to these materials has been linked to systemic health impacts including: compromised immune, cardiovascular, renal, gastrointestinal, neurological, reproductive, endocrine and respiratory functions; sensory organ impairment; hepatic and renal dysfunction; carcinogenic effects; neurodevelopmental toxicity; reduced birth weight; dermatological irritation; and metabolic disorders like diabetes (Maennel et al., 2019).

In terrestrial ecosystems, microplastics originating from degraded consumer products like polymer-coated tea bags and disposable cups migrate into aquatic systems through multiple vectors - including leaching, flood events, and aeolian transport. These particles subsequently contaminate freshwater reservoirs, wastewater systems, and marine habitats as persistent pollutants. Within marine ecosystems, microplastics disrupt phytoplankton and zooplankton populations - organisms that are vital for oceanic carbon cycling and sequestration through the biological carbon pump mechanism (Kumar and Verma, 2025)

Research by Shen et al. (2020)²⁴ demonstrates that microplastics impair phytoplankton growth, reducing oceanic CO₂ uptake and compromising a critical natural carbon sink. This phenomenon exacerbates climate change by weakening the planet's capacity to regulate atmospheric carbon levels. Beyond ecological impacts, microplastics pose direct risks to human health. For instance, ions leaching from paper cups into beverages can elevate their concentrations, potentially introducing undesirable chemical exposure.

Microplastics also serve as carriers for toxic pollutants, including phenanthrene, heavy metals, antibiotics, and polybrominated diphenyl ethers (PBDEs) (Kumar and Verma, 2025). These complex contaminant mixtures threaten terrestrial

and aquatic ecosystems alike. In marine environments, microplastics are inadvertently or intentionally ingested by fish, entering the human food chain and raising global food safety concerns (Li et al., 2022; Clere et al., 2022).

The problem is further compounded in regions facing water scarcity. Farmers in developing countries, such as India, often irrigate crops with sewage wastewater (SWW) due to freshwater shortages, despite its high pollutant load (Kumar and Verma, 2025)⁹. Additionally, SWW discharge into freshwater sources leads to microplastic and nanoplastic contamination in drinking water, creating long-term health risks for communities reliant on these supplies.

Almroth et al. (2023)²⁷ investigated the environmental implications of disposable takeaway cups and lids composed of plastic or paper, with a particular emphasis on their capacity to leach hazardous substances. The study assessed leachates derived from polypropylene (PP) plastic cups, polystyrene (PS) lids, and polylactic acid (PLA)-lined paper cups under conditions designed to simulate leaching in natural aquatic environments. Toxicity was evaluated using *Chironomus riparius*, a model aquatic invertebrate, with multiple biological endpoints examined, including larval development, growth, and adult emergence. The results indicate that single-use beverage cups, irrespective of material composition, elicit toxic effects in aquatic midges. Further analysis demonstrated teratogenic responses, with significant mouthpart deformities observed in larvae exposed to leachates from polystyrene lids in sediment. Additionally, female midges exposed to sediment-containing leachates from paper cups exhibited a marked delay in emergence.

Eid et al. (2025)²⁸ investigated the leaching of microplastics, ions, and heavy metals from paper cups into aquatic environments and their subsequent effects on fish. The study utilized Nile River water samples from Assiut, Egypt, to assess contamination levels, with shredded paper cups serving as the test material. Analysis of two local fish species *Oreochromis niloticus* and *Bagrus*

bajad revealed significant microplastic accumulation in intestinal tissues. Polyethylene (PE), polystyrene (PS), and polypropylene (PP) were the predominant microplastics identified in water samples, underscoring the role of paper cups in polluting the Nile River and posing risks to aquatic organisms.

In a related study, Banaei et al. (2023)²⁹ examined the release of micro- and nanoplastics (MNPLs) from commercial tea bags and their effects on intestinal cell models, including undifferentiated Caco-2 and HT29 monocultures, as well as a Caco-2/HT29 co-culture barrier system. The research evaluated PLA-derived nanoplastic (PLA-NPL) uptake, cytotoxicity, oxidative stress, and barrier integrity. Findings indicated high particle internalization, particularly in mucus-secreting cells, with persistence in tissues for up to 72 hours. While no significant cytotoxicity was observed at concentrations of 100 µg/mL over 48 hours, minor barrier disruption was detected at earlier exposure intervals.

Despite growing recognition of the environmental consequences of plastic pollution, global governance mechanisms remain insufficient in curbing its escalation in marine ecosystems (Dauvergne, 2018, Rashid and Ismail, 2022; Ahmed et al., 2025; Rashid and Hamad, 2023). Key challenges include: a) Toxicity - Plastics release harmful additives and adsorb pollutants. b) Malleability and Durability - Their persistence in the environment spans centuries. c) Degradation Pathways - Photodegradation fragments plastics into microplastics (MPs) and nanoplastics (NPs), while cold, dark marine conditions slow disintegration. d) Particle Size - Secondary MPs (<5 mm) form via fragmentation, whereas primary MPs (e.g., microbeads, fibers) enter ecosystems already in microscopic form.

Additionally, paper cup disposal—primarily via landfilling, may contribute to terrestrial microplastic contamination through particle loss, improper waste handling, and aerosol generation (Souza Machado et al., 2018). While landfilling dominates paper cup waste management, it also

exacerbates spatial demands in landfills. Crucially, current life cycle assessment (LCA) methodologies cannot quantify the full impact of (micro)plastic pollution, leaving critical knowledge gaps in their environmental footprint.

Conclusions

This systematic review highlights the significant environmental and public health risks posed by microplastics (MPs) and associated toxic compounds leaching from disposable paper cups and plastic beverage containers. Key findings include:

MPs (1 μm –5 mm) and nanoplastics (<1 μm) migrate into beverages through thermal degradation, mechanical stress, and chemical interactions, with studies detecting up to 25,000 particles per cup after 15 minutes of exposure. MPs contaminate aquatic and terrestrial ecosystems, acting as vectors for heavy metals and persistent organic pollutants (POPs), which bioaccumulate in marine organisms and enter the human food chain. Toxicological studies demonstrate cellular uptake, oxidative stress, and metabolic disruption in human cell lines (e.g., Caco-2, HT29) and aquatic species at concentrations as low as 10–100 $\mu\text{g}/\text{mL}$. Human exposure estimates suggest daily ingestion of 100–500 MPs particles from beverage containers alone, linked to inflammatory responses, endocrine disruption, and systemic health effects (e.g., hepatic, renal, and neurological dysfunction). Environmental degradation of MPs contributes to climate change by releasing greenhouse gases (CO_2 , CH_4) and disrupting carbon sequestration processes in soil and marine ecosystems.

Recommendations

Policy and Regulatory Actions; Implement strict regulations on plastic additives (e.g., phthalates, bisphenol A) in food packaging. Enforce extended producer responsibility (EPR) schemes to ensure proper recycling and waste management of disposable cups.

Technological Innovations; Develop biodegradable or edible cup linings as alternatives to polyethylene (PE) and polystyrene (PS). Invest in advanced filtration systems to remove MPs from water supplies and wastewater treatment plants.

Public Awareness and Behavior Change; Launch campaigns promoting reusable containers (e.g., stainless steel, glass) and discourage single-use cup consumption. Educate consumers on the health and environmental risks of hot beverages in disposable cups.

Research Priorities; Standardize MP detection methods and toxicity assessment protocols.

Investigate long-term health impacts of chronic MP exposure in humans. Explore eco-friendly materials for beverage packaging with minimal leaching potential.

Environmental Remediation; Expand large-scale recycling programs for paper and plastic cups, with incentives for participation. Monitor and remediate MP hotspots in aquatic and terrestrial ecosystems.

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