Microplastics Occurrence, Health Effects, and Mitigation Policies

An Evidence Review for the California State Legislature

January 2023

CalSPEC

About CalSPEC

The California State Policy Evidence Consortium (CalSPEC) is a University of California (UC) initiative administered through the UC Center Sacramento (UCCS). In alignment with the UC mission, CalSPEC leverages UC expertise in research and commitment to public service to support evidence-based policymaking at the state level. Specifically, CalSPEC seeks to build an evidence pipeline to the State Legislature that enhances policy decision-making through rapid evidence and policy reviews on complex topics of concern or interest to the State Legislature. CalSPEC engages a team of expert UC faculty and staff who collaborate with legislative committee staff to determine the key analytic questions and ultimately produce balanced, nonpartisan, evidence-based reports within a California legislative cycle.

More detailed information about CalSPEC is available at https://uccs.ucdavis.edu/calspec.

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EXECUTIVE SUMMARY

This report responds to a joint request from the California Senate Committee on Environmental Quality and the Assembly Committee on Natural Resources for evidence concerning human health effects of microplastics and public policies related to microplastics prevention and mitigation. Research was conducted by the California State Policy Evidence Consortium (CalSPEC), an independent program administered through the University of California Center Sacramento (UCCS) and composed of faculty, staff, and graduate student researchers across UC campuses who evaluate evidence to inform public policy deliberations.

This report addresses three overarching questions:

1. What are microplastics and how abundant are they in the environment?

2. What are the human health effects from microplastics exposure?

3. What government actions have addressed microplastics, and to what extent have the policies succeeded in reducing microplastics in the environment?

Overview of Microplastics

- Plastics persist and accumulate in the environment regardless of whether disposal is managed or unmanaged.
    - Annual global plastic production, increasing exponentially since 1990, will reach an estimated 1.1 billion metric tons by 2050.
    - Degradation studies estimate the half-lives of plastics in the natural environment range from 50 to 1200 years, depending on the plastic's composition and environmental exposures.
    - Plastics generated 1.8 billion metric tons of greenhouse gas (GHG) emissions in 2019, which represents 3.4% of global GHG (more than the percentage of $C0_2$ contributed by the global aviation industry); annual emissions from plastics will exceed 4.3 billion metric tons by 2060.
- Once plastics enter the environment (air, water, soil, food, flora/fauna), they break into smaller fragments — microplastics — enabling long-range transport, which increases environmental and human interactions. A growing body of evidence shows increasing human exposure to microplastics due to accumulation in the ecosystem.
- The packaging and textiles sectors are the largest contributors to microplastics waste.
- Microplastics are small particles, generally defined as <5 mm (5,000 microns)[1] in one dimension. They are either:
    - *Primary microplastics*: intentionally manufactured microplastics, such as preproduction feedstock (pellets) for plastics manufacturing, microbeads (for abrasion in cosmetic

[1] For this report, CalSPEC uses a modified version of the microplastic definition developed by the California State Water Resources Control Board for drinking water.

personal care products and industrial cleaners), particles for air-blasting technology and printer toner; or films or resins (coatings for seeds or fertilizers).

- *Secondary microplastics*: fragments degraded from larger products that contain plastics including packaging, tires, and textiles.

- Microplastics differ in size, shape (beads, pellets, fibers, fragments, films, etc.), and chemical composition. These characteristics affect transport, fate, and persistence in the environment.
- Microplastics cross geographic and environmental boundaries and have been found everywhere they have been studied, including Arctic glaciers and deep-sea sediment. The totality of their prevalence globally and environmental and health impacts remain unknown. However:
  - Secondary microplastics are thought to comprise the majority of microplastics in the environment. For example, two-thirds of microplastics in the global marine environment are from fragmentation of virgin plastics such as tires, synthetic textiles, packaging, road markings, and marine coatings. Virgin plastics are polymers or resins that have never been used or processed before.
  - Microplastics annually released to land are estimated to be 4 to 23 times greater than microplastics released to oceans.
- Microplastics research is an emerging field dominated more by studies of occurrence and polymer type than intermediate and long-term environmental and health effects. The field is working to standardize scientific definitions, research methods, and units of measurement.

Health Effects of Microplastics

CalSPEC conducted a rapid systematic review of evidence from the peer-reviewed literature to answer: "What are the human health effects from microplastics exposure?" A comprehensive search in July 2022 found no human studies of microplastics exposure; therefore, CalSPEC used a well-established scientific method to evaluate mammalian rodent studies of microplastic exposures. This process allowed CalSPEC to draw conclusions about human health effects.

Of the multiple biologic systems studied, this rapid review used a stepped approach to evaluate the effects of microplastics on human digestive, reproductive, and respiratory systems. CalSPEC evaluated the quality and strength of the evidence for outcomes related to biological changes (e.g., immunologic responses, inflammatory responses, hormonal changes) and observable outcomes (e.g., colon shortening, sperm damage) measured in studies meeting the search criteria.

CalSPEC then characterized the evidence into one of three human health hazard level classifications based the animal data: 1. Presumed to be a hazard to humans; 2. Suspected to be a hazard to humans; 3. Not Classifiable using the Hazard Identification Scheme from the National Toxicology Program as guidance.

Key Findings

- The evaluated evidence was of primarily moderate quality based on criteria from the UCSF Navigation Guide methodology.

- Exposure to microplastics is suspected to be a digestive hazard to humans, including cancer.
- Exposure to microplastics is suspected to be a hazard to the human reproductive system.
- Although the evidence from the respiratory studies did not undergo as rigorous of an evaluation, the findings in the five studies on the respiratory system are also indicative of health harm.
- Limitations: This rapid review did not evaluate all health outcomes in the digestive and reproductive systems and did not evaluate plastic chemical additives known to increase the risk of negative health effects. There may also be adverse health outcomes in systems not evaluated. CalSPEC recognizes that the conclusions of the rapid review can be an underestimation of the true harm of microplastic exposure given these limitations.

Microplastics Policies at the National, Subnational, and Multinational Levels

Chapter 4: Microplastics Policies describes government actions regarding microplastics including mandates for research to understand the environmental and human health impacts of microplastics; bans and regulations of microplastics by source (microbeads, textiles, and tires); and a high-level overview of multinational agreements or treaties on microplastics. CalSPEC also searched for evaluations of policy effectiveness.

Key Findings

CalSPEC found 51 laws addressing microplastics across various levels of government and jurisdictions. The majority are concentrated in Europe and in California and are focused on banning microbeads or mandating more research.[2]

In summary:

- National and subnational governments are beginning to recognize the scale and impact of microplastics degradation and have mandated research, measurement standards, and funding opportunities to mitigate and/or prevent microplastic occurrence within or among environmental compartments.
- Policies are generally siloed by environmental compartment and/or microplastic source, often within a specific geographic area, rather than using a cross-boundary, ecosystem approach.
- Initial efforts to address microplastic mitigation/prevention focused on banning microbeads in cosmetics.
- Recent research on the threat of textile-derived microplastics to waterways led to new but limited requirements for microplastic filtration devices on washing machines.
- CalSPEC did not identify any empirical evaluations assessing the effectiveness of the policies included herein. CalSPEC presents three empirical evaluations of macroplastics (mainly

[2] CalSPEC excluded macroplastic policies (e.g., plastic bags, single-use containers, etc., which are known to break down into microplastics). Efforts to control macroplastic release into the environment — principally through recycling mandates, bans, and user fees — are beyond the scope of this report.

plastic bag) policies and interventions, which are presented only as potential models for microplastics policy evaluation.

Report Conclusions

This report renders three principal conclusions. First, knowledge about microplastics prevalence, distribution, and toxicity to humans is incomplete. Second, despite these knowledge gaps, existing evidence raises concerns about the environmental and health consequences of microplastics pollution. Third, the international community has only just begun to implement policy interventions designed to curtail microplastics pollution, but the effectiveness of these interventions is unknown.

More research is needed to characterize the prevalence and distribution of microplastic contaminants across all environmental compartments, determine acceptable levels of microplastics exposure to humans and the environment, and evaluate effective prevention and mitigation techniques. While responsibility for funding most scientific research falls to the federal government, California could spur research in this area by funding pilot projects at California universities, perhaps modeled after the Tobacco-Related Diseases Research Program or the new UC Climate Action Research Initiative.

Despite gaps in the available evidence, the precautionary principle suggests that California consider advancing policies that limit microplastic exposure. Some degree of urgency is warranted both because of the long lead time required to reduce (micro)plastic pollution and the long half-life (measured up to centuries) of plastic pollutants. As policies are implemented, it is vital that rigorous research be conducted to quickly identify the policies that are most effective and efficient at reducing microplastics contamination, at what cost, and with what tradeoffs. Some of the needed information can be derived from economic modelling studies, but policy evaluations using strong cluster-randomized or quasi-experimental designs are also needed.

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GLOSSARY

Adverse health outcomes: based upon the United States Environmental Protection Agency and California law definitions, a biochemical change, functional impairment, or pathological lesion affecting the performance of the whole organism or reducing an organism's ability to respond to additional environmental challenges.

Apical endpoints: observable outcomes in an organism (such as a clinical sign or pathological state) that indicate disease.

Association of Southeast Asian Nations (ASEAN): brings together 10 Southeast Asian countries (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam) into one collective decision-making body to facilitate economic, political, educational, and sociocultural cooperation.

Bioaccumulation: organisms absorb toxic substances from the environment faster than they excrete or metabolize them and contribute to biomagnification.

Biological change: outcomes in an organism that are not observable (such as changes to gene expression).

Biomagnification: Toxic substances increase in concentration as they are passed up the food chain.

Circular economy: recognizes waste as an economic resource and by shifting the focus to utilizing recycled materials in the manufacturing of new products.

Conference of the Parties (COP): the decision-making body responsible for monitoring and reviewing the implementation of the United Nations Framework Convention on Climate Change. COP convenes 197 nations and territories, called "Parties," that have signed on to the Framework Convention. The 21st Session of the COP (COP21), held in 2015 in Paris, France, was where the first multinational climate agreement was signed.

Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Commission: This 1992 agreement between 15 governments and the European Union commits to protecting the marine environment of the North-East Atlantic. Signatories include Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom.

Interagency Marine Debris Coordinating Committee (IMDCC): a multi-agency body that coordinates marine debris research and activities among US executive branch agencies, in cooperation and coordination with nongovernmental organizations, industry, academia, states, tribes, and other nations, as appropriate. They are located within the National Oceanic and Atmospheric Administration (NOAA), within the Marine Debris Program.

Key characteristics: mechanisms or biological pathways that are known to be linked to systemic or observable endpoints, including cancer and adverse reproductive health outcomes. The following table describes the 10 characteristics relevant to CalSPEC's evaluation of microplastics on human health.

Key Characteristic of Carcinogens	Key Characteristic of Reproductive Toxicants (Male)	Key Characteristic of Reproductive Toxicants (Female)	Definition
Electrophilic or metabolically activated	–	–	Forms addition products, often referred to as adducts, with DNA and other molecules (RNA, lipids, and proteins)
Genotoxic	Is genotoxic	Chemical or metabolite is genotoxic	Causes DNA damage and/or mutation
Alters DNA repair or causes genomic instability	–	–	Alters the repair of DNA damage or disrupts the stability of the genome
Induces epigenetic alterations	Induces epigenetic alterations	Induces epigenetic alterations	Impacts gene expression without affecting the DNA sequence
Induces oxidative stress	Induces oxidative stress	Induces oxidative stress	Disrupts the balance of production and detoxification of reactive oxygen species
Induces chronic inflammation	Induces inflammation		Causes a prolonged inflammatory response
Is immuno-suppressive	–	Alters immune function	Suppresses immune surveillance of cancer cells; alters immune system function
Modulates receptor-mediated effects	Alters production and levels of reproductive hormones OR Alters hormone receptor levels/functions	Alters hormone receptor signaling; alters reproductive hormone production, secretion, or metabolism	Changes processes, such as hormone actions, that are controlled through receptors
Causes immortalization	–	–	Increases the life span of tumor cells so they replicate indefinitely
Alters cell proliferation, cell death, or nutrient supply	Alters germ cell development, function, or death OR alters somatic cell development, functions, or death	Alters survival, proliferation, cell death, or metabolic pathways	Promotes the growth of tumor cells and helps them evade death; alters the growth, function, or development of germ cells or somatic cells

Source: CalSPEC, 2023, based on Arzuaga et al., 2019; Luderer et al., 2019; Smith Martyn et al., 2016.

Note: Additional key characteristics that have been identified for female reproductive toxicity, but are not reviewed in this report, include causes mitochondrial dysfunction, alters cell signal transduction, alters direct cell-cell interactions, and alters microtubules and associated structures.

Literature review: a review and synthesis of available evidence relevant to a specific research question that does not include an evaluation of the quality of the evidence; may also be referred to as a narrative review.

Megaplastics: no standardized definition exists, but The Ocean Cleanup[3] and Handbook of Microplastics in the Environment[4] define it as particles greater than 50 cm in diameter.

Microplastics: CalSPEC uses the definition from the California State Water Resources Control Board's Policy Handbook Establishing a Standard Method of Testing and Reporting of Microplastics

[3] The Ocean Cleanup: https://theoceancleanup.com
[4] Handbook of Microplastics in the Environment: Handbook of Microplastics in the Environment | SpringerLink

in Drinking Water[5] (includes nanoplastics, mesoplastics, and macroplastics as well) and modified the definition to include particles less than <5 mm (5,000 microns) in one dimension and particles of any composition with polymer content.

- *Primary microplastics:* intentionally manufactured microplastics, such as preproduction feedstock (pellets) for plastics manufacturing, microbeads (for abrasion in cosmetic personal care products and industrial cleaners), particles for air-blasting technology and printer toner; or films or resins (coatings for seeds or fertilizers).
- *Secondary microplastics:* microplastics generated from the degradation of plastic products, such as packaging, synthetic textiles, rope, or tires and brakes (including dust from braking, and recycled rubber granulate for athletic turf and playgrounds).

Ocean Protection Council (OPC): Established through the 2004 California Ocean Protection Act, this seven member council is housed in the California Natural Resources agency and is tasked with: 1) Coordinating activities of ocean-related state agencies to improve state efforts to protect ocean resources within existing fiscal limitations; 2) Establishing policies to coordinate the collection and sharing of scientific data related to coastal and ocean resources between agencies; 3) Recommending to the Legislature changes in law; and 4) Recommending changes in federal law and policy to the Governor and Legislature.

Protocol: document that is made publicly available to outline the steps of a systematic review (including rapid reviews) before the review is completed.

Quality of evidence assessment: the critical appraisal of included studies to evaluate the extent to which study authors conducted their research to the highest possible standard.

Rapid systematic review (rapid review): a truncated form of a systematic review that is used when there is a time-sensitive question to address, and quality systematic reviews are not available.

Risk of bias: (sometimes referred to as "internal study validity"), a critical assessment of whether the design or conduct of a study could systematically change the reported association between exposure and outcome.

Secretariat of the Pacific Regional Environment Program (SPREP): a regional entity based in Samoa focused on climate change and environmental issues affecting small island developing states. The 21 Pacific Island member countries include American Samoa, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, Niue, Northern Marianas, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, and Wallis & Futuna.

Strength of evidence assessment: the conclusion of a systematic or rapid review that considers the quality of the evidence, the direction of effect estimates, confidence in effect estimates, and other compelling attributes of the evidence.

Systematic review: synthesizes all available evidence relevant to a specific research question and evaluates the quality of the evidence. Systematic reviews provide an overview of what is known and what is not known about a topic. Their main advantages over less formal "narrative" reviews are comprehensiveness, transparency, consistency, reproducibility, and controls for bias.

United Nations Environment Assembly (UNEA): the world's highest-level decision-making body on the environment, with a universal membership of all 193 Member States. UNEA meets biennially

[5] California State Water Resources Control Board's Policy Handbook Establishing a Standard Method of Testing and Reporting of Microplastics in Drinking Water: [Resolution Adopting a Policy Handbook Establishing a Standard Method of Testing and Reporting of Microplastics in Drinking Water (ca.gov)]

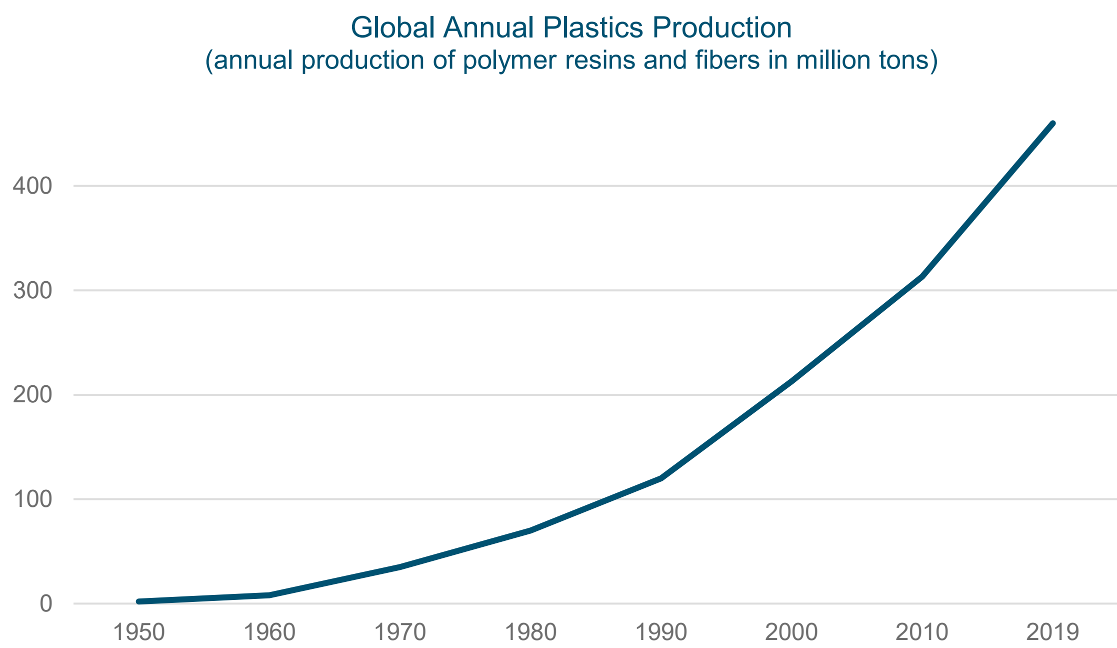
in Nairobi, Kenya, to set priorities for global environmental policies and develop multinational environmental law. UNEA provides leadership and catalyzes intergovernmental action on the environment. UNEA is also the governing body of the United Nations Environment Program. It has had five sessions starting in 2014 and was preceded by the Governing Council of the UN Environment Program, which was composed of 58 member States.

United Nations Environmental Program (UNEP): founded in 1972, UNEP is the global authority that sets the environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations and serves as an authoritative advocate for the global environment.

CHAPTER 1: INTRODUCTION

Plastics are ubiquitous in modern society. Their use has increased exponentially over the past 20 years, in large part due to perceived benefits including efficiency, durability, and convenience (Figure 1) (Geyer, 2020; Sangkham et al., 2022). However, since the 1997 discovery of the "Great Pacific Garbage Patch," public awareness of the prevalence and harms of plastic pollution has been growing. An especially salient issue is the pervasiveness of small plastic particles (generally less than 5 mm in diameter) known collectively as "microplastics." Research shows a wide global distribution and increasing accumulation of microplastics across all environmental compartments: in the air (atmospheric), on land (terrestrial), in the water (aquatic), and within living organisms, including plants and animals (biota) (Geyer, 2020; Lau and Murphy, 2021).

Figure 1. Global Annual Plastics Production Has Been Increasing Exponentially



Source: CalSPEC, 2023, based on Ritchie and Roser, 2018, and Geyer et al., 2020.

Concerns about negative impacts of microplastics on the environment and ultimately on human health led the California State Legislature to investigate and address the potentially harmful effects of microplastics through several legislative acts. For example, AB 258 (CA Legislature, 2007) restricted discharges of preproduction plastics (microplastic pellets and colorants used for plastics production) to waterways that occur during the manufacturing, handling, and transporting process; AB 888 (CA Legislature, 2015) restricted sale of personal care products containing microbeads; SB 1422 (CA Legislature, 2018) instructed the State Water Resources Control Board to adopt a standardized microplastics definition and drinking water testing procedures; and SB 1263 (CA Legislature, 2018) requested the California Ocean Protection Council (OPC) to create a statewide microplastics strategy to protect aquatic ecosystems by 2021, as well as provide recommendations for policy changes by 2025 (OPC, 2022; SCCWRP, 2022) (see *Chapter 4: Microplastics Policies* for details).

Given continued interest from the California State Legislature, this CalSPEC report responds to a joint inquiry from the California Senate Committee on Environmental Quality and Assembly Committee on Natural Resources about evidence concerning human health effects of microplastics and public policies related to microplastics prevention and mitigation.

Specifically, this peer-reviewed report provides foundational information about microplastic composition and prevalence (occurrence); a rapid systematic review of health effects of microplastics; and a review of multinational, national, and subnational microplastic policies. In alignment with the CalSPEC mission, the report is intended to support evidence-based deliberations to analyze and inform California state policy; it may also be applicable to California local governments and jurisdictions outside of the state.

This report addresses three overarching questions:

1. What are microplastics and how abundant are they in the environment?

2. What are the human health effects from microplastics exposure?

3. What government actions have addressed microplastics, and to what extent have the policies succeeded in reducing microplastics in the environment?

These key questions were developed through a collaboration between California state legislative committee staff and UC researchers. A UC librarian executed the literature searches based on specifications from the research team. Using results from literature searches, the multi-campus UC research team evaluated the available evidence to inform stakeholder discussion about the magnitude of the microplastics issue and potential policy solutions. To the extent possible, CalSPEC uses systematic and reproducible methods for obtaining, reviewing, and summarizing published evidence. However, owing to the compressed timeframe available for production of this report, each of the three substantive chapters use different methods customized to their objectives.

Chapter 2: Microplastics Explained provides foundational information from peer-reviewed and grey literature (reports sponsored by government agencies, foundations, nonprofit organizations) describing microplastics and their presence in the environment.

Chapter 3: Health Effects of Microplastics is organized as a rapid systematic review (methods used detailed in the Human Health Effects of Microplastics: Rapid Review Protocol[6]). The subsection on digestive and reproductive effects combined systematic article retrieval, rigorous quality assessment, and standardized evidence synthesis. Due to time constraints, the subsection on respiratory effects used the same retrieval methods, no quality assessment, and a narrative synthesis.

Chapter 4: Microplastics Policies is organized as a rapid policy review with narrative synthesis of multinational, national, and state policies.

Chapter 5: Report Conclusion includes statements about the quality, strength, and direction of the research evidence on health and prevention and mitigation policies but refrains from providing direct recommendations. Information herein is designed to inform policy development and foster debate based on the best available current evidence.

[6] Available on Open Science Framework at https://osf.io/cwu87

A microplastics content expert provided subject matter support throughout the report process including a review of the draft report. Four external subject matter experts, unrelated to this project, reviewed the report. The CalSPEC Consortium Advisory Council and Faculty Steering Committee also reviewed the report for clarity, neutrality, and responsiveness to the legislative request.

Defining Scope of Inquiry

There are several important limits to the report's scope of inquiry. This report focuses on microplastics defined as particles less than 5 mm in one dimension. To comport as closely as possible with California policy while being as inclusive as possible of peer-reviewed literature, CalSPEC slightly modified the California State Water Resources Control Board (SWRCB) definition by removing the board's lower dimension boundary and including all microplastics regardless of percent content of polymer. The CalSPEC definition accommodates the challenges associated with measurement and allows for inclusion of microplastics from surface coatings or tire wear.

This report focuses on microplastics; the direct environmental and health effects of plastic products (so-called macroplastics and megaplastics) from which most microplastics are derived are beyond the scope of this report.[7]

Definition of Microplastics

Based on the definition from the California State Water Resources Control Board, CalSPEC defines microplastic as:

- Solid polymeric materials to which chemical additives or other substances may have been added, and
- Which are particles less than 5 millimeters (mm) in one dimension (also referred to as 5,000 microns (μm).

[7] Megaplastics (diameters >50 cm) have received significant attention over the last 25 years with California and other jurisdictions taking steps to prevent and mitigate pollution stemming from plastic trash. Collectively and informally known as the California Trash Amendments, these include bans on single-use plastics, and mandatory and voluntary recycling and reuse programs. For more details, see the California State Water Resources Control Board's Statewide Water Quality Control Plans for Trash, available at https://www.waterboards.ca.gov/water_issues/programs/trash_control/documentation.html.

CHAPTER 2: MICROPLASTICS EXPLAINED

The study of microplastics is a rapidly emerging field.[8] Most research has focused on occurrence (counts) and size (volume, density, and/or mass) of plastic particles within various environmental compartments in different geographic locations. Significant research challenges remain (e.g., standardized definitions, units of measurement, research methods) and initial findings about environmental and human health impacts are only beginning to emerge.

This chapter provides foundational information for the subsequent report chapters that explore the health effects of microplastics and policies to prevent and mitigate potentially negative environmental and health effects. It summarizes information about microplastics production, composition, persistence, transit, and fate in the environment. Information in this chapter ultimately describes, for stakeholder consideration, various points of intersection should policy interventions be warranted.

Plastics Composition, Production, and Accumulation

Although this report does not focus on virgin plastics (new polymers created from raw materials [petrochemicals] without any recycled materials [Grabiel et al., 2022]), this short section presents contextual information about the upstream source of microplastic particles.

The resilience and durability of plastics contributes some societal and economic benefits, such as improvements in health and safety, energy savings (due to light weight), and material conservation (Andrady and Neal, 2009). However, researchers are uncovering some consequences of plastics. Their stubborn degradation characteristics lead to an unwanted persistence of plastic waste in the environment (Ritchie and Roser, 2018). Once plastics enter the environment, they break into smaller fragments — microplastics — enabling long-range transport, which increases environmental and human interactions (Fan et al., 2019; Galloway et al., 2017). A growing body of evidence shows increasing human exposure to microplastics due to accumulation in the ecosystem and food webs (Desforges et al., 2015).

Plastics Composition and Production

Like all manufactured products, plastics have a life cycle beginning with extraction of raw materials and ending with disposal (Kumar et al., 2021).

> *Stage 1: Extracting and manufacturing raw materials.* The majority of first-generation (virgin) plastics are synthesized from fossil fuels (oil, coal, or natural gas), while some are biobased[9] (renewable) substances from plants (cellulose), trees (latex), animals (milk and hooves), and insects (shellac) (Baheti, 2022; CIEL, 2017; Lamichhane et al., 2022). These organic monomer sources are joined into polymers, long repeating chains of molecules to which other chemicals are added to form plastics with different properties (e.g., elasticity, strength, density) (Chamas et al., 2020; Gad, 2014; Rodriguez, 2022).

[8] Microplastic research publications accelerated from 100 in 2014 to approximately 2000 in 2020; there are nascent efforts for data sharing among researchers in an attempt to improve standardization of measurement and reporting outcomes (Bakhshoodeh and Santos, 2022; Jenkins et al., 2022)

[9] Biobased products are equally resistant to biodegradation and require industrial composting (NOAA, 2022).

Stage 2: Production of plastic products using plastic pellets. Pellets or nurdles are preproduction material also known as "feedstock" that are uniform in shape and size. They are commonly melted and molded into larger shapes by molders and 3D printers to produce a variety of plastic products. Pellets may also be used in consumer products such as weighted blankets, toys, and bean bag chairs.

Stage 3: Purchase and consumption (industrial and consumer). The useful life span of plastic products varies widely (e.g., <6 months for packaging versus ~35 years for appliances and construction materials) (Geyer, 2020).

Stage 4: End-of-life disposal (managed and unmanaged). The end of the plastic life cycle occurs through managed and unmanaged disposal of plastic products. Managed disposal uses recycling, landfill placement, or incineration. The true global distribution of plastics at end of life is unknown; estimates vary based on geographic location, compartment, and definitions of disposal. See "Accumulation and Persistence of Plastic" below.

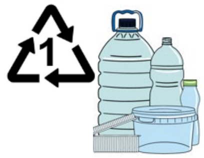
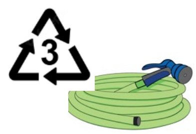
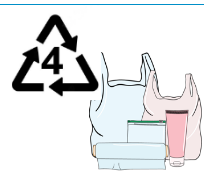
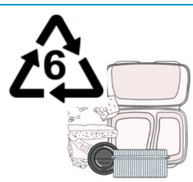
Table 1 describes the seven most common types of plastic polymers in production globally and their uses. The type of polymer selected for manufacturing is based on the functional needs of the product, the mode of production, and production costs relative to product value (Kumar et al., 2021). For example, does the container need to be rigid or flexible (water bottle or bags)? Heat-proof or waterproof (automotive parts, marine equipment)? Durable or single use (appliance or drinking straw)? Polymers are classified according to the numeric *Resin Identification Code* system, which simply identifies a product by its dominant polymer. This system has been repurposed by recycling programs as a simple but not entirely accurate resource for consumers to identify potentially recyclable products.

In addition to the type of polymer, plastics can include numerous additives such as plasticizers, flame retardants, antioxidants, and pigments that are added to improve product function, resilience, and look. For example, some polymers contain per- and polyfluoroalkyl substances (PFAS), chemicals that resist heat, oil, stains, grease, and water, which are used in coatings and products such as clothing, food packaging, nonstick cooking surfaces. These substances are suspected to be carcinogenic and immunosuppressive (CDC, 2022a).

Accumulation and Persistence of Plastic

As depicted in Figure 1 (*Chapter 1: Introduction*), global reliance on plastic products has grown dramatically since 1950 and especially since 1990. Assuming similar growth and demand patterns in the future, projections estimate annual plastic production will reach 1.1 billion metric tons by 2050 (Geyer, 2020). Degradation studies estimate the half-lives of plastics in the natural environment range from 50 to 1200 years, depending on the plastic's composition and environmental exposures (Chamas et al., 2020).

Table 1. Summary of Types of Polymers Used to Make Plastic Products and Their Recyclability

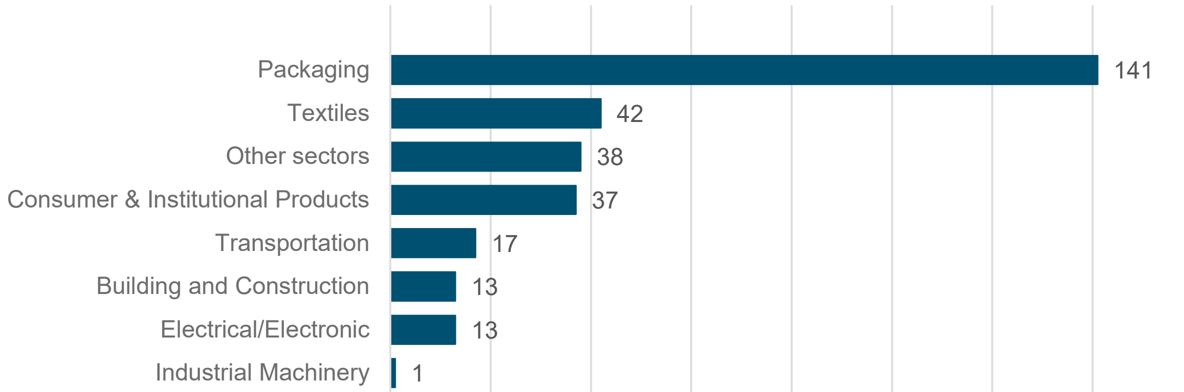
Polymer Type[a]	Resin identification code[a]	Product Examples[a]	% of Plastics Production by Polymer Type[b]	Recyclability[c]
Polyethylene terephthalate (PET/PETE)		Water/juice/soft drink bottles, ovenable/microwaveable food trays, carryout food containers, shampoo bottles, carpet, films, synthetic clothing (polyester)	26.7% (*in combination with PP*)	Commonly recycled (represents 18.5% of US municipal plastic waste recycled)
High density polyethylene (HDPE)		Toys, reusable water bottles, food storage containers, cereal box liners, wire/cable covering, outdoor signage	12.3%	Commonly recycled (represents 8.9% of US municipal waste recycled[d])
Polyvinyl chloride (PVC)		Packaging (clam shells, shrink wrap) rigid pipes, flooring, building siding, wire insulation, garden hoses, gutters, medical products	10%	Difficult to recycle, not universally collected for recycling
Low density polyethylene (LDPE)		Plastic film/baggies (dry cleaning, newspapers, garbage bags), single-use bags, juice boxes, wire insulation, container lids, toys, shrink wrap, beverage cup liners	17.5%	Difficult to recycle, not universally collected for recycling (represents 4.3% of US municipal waste recycled[d])
Polypropylene (PP)		Carpet, rope, luggage, marine equipment, appliances, straws, medical components, plastic caps/lids, carpeting	26.7% (*in combination with PET*)	Difficult to recycle, not universally collected for recycling (represents 0.6% U.S. municipal waste recycled[d])
Polystyrene (PS)		Car parts, appliances, TVs/computers, medical lab equipment, carryout food containers (Styrofoam™), yogurt containers, cups/plates/utensils, packing peanuts, egg cartons	6.3%	Difficult to recycle, not universally collected for recycling (represents 0.9% of US municipal waste recycled[d])
Other (e.g., polycarbonate [PC]; polylactic acid [bioplastic PLA]; poly methyl acrylate [PMA]; polyamide [PA]; polyvinyl alcohol [PVA])		Safety shields/glasses, toys, oven-baking bags, 3/5 gallon reusable water jugs, ketchup bottles, custom packing, synthetic clothing (nylon and acrylic), detergent pods, resins/paints, automotive, safety glass	27.2%	Difficult to recycle because the number does not specify which of the many polymer types covered; may also indicate combined polymers, which are not recyclable

Source: CalSPEC, 2022 based on a) NOAA, 2018; b) EPA, 2022c; c) Magalhaes et al., 2020; d) EPA, 2020.

Note: Images from Shutterstock, 2023.

Between 1950 and 2015, researchers estimate that manufacturers have produced 9,500 million metric tons of virgin plastic (~1 ton per person globally) resulting in ~6,300 million metric tons of plastic waste in the environment today. Today, 10%–18% of plastics are recycled globally and about 24% are incinerated (Geyer et al., 2017; Ritchie and Roser, 2018) with the rest of the waste deposited in landfills or in the natural environment. Figure 2 shows the global waste contribution in 2015 by industry category with packaging and (synthetic) textiles as the leading contributors to plastic waste.

Figure 2. Plastic Waste by Industrial Sector (in million metric tons), 2015



Source: Geyer et al., 2017, and Ritchie and Roser, 2018.

Impacts of Plastics on Climate

This report focuses on the human health effects of microplastics and related policies rather than the environmental impacts of microplastics; however, CalSPEC acknowledges the growing body of research on the effects of microplastics in the environment, including climate change. The Organisation for Economic Co-operation and Development (OECD) estimates that plastics generated 1.8 billion metric tons of greenhouse gas (GHG) emissions in 2019, representing 3.4% of global GHG (OECD, 2022). By 2060, GHG emissions from plastics are projected to more than double (4.3 billion metric tons) with about 0.5 billion metric tons of GHG attributed to end-of-life management (e.g., litter, incineration emissions). Accumulation of microplastics in the Arctic are suspected to contribute to accelerated warming by blocking the reflective capacity of snow (OECD, 2022). Other examples of impacts include microplastics inhibiting algae growth by ~40% at higher concentrations (5 mg/L vs 50 mg/L), which may reduce the carbon sequestration efficiency of algae (Zhang et al., 2017).

Once plastics enter the environment, they break into smaller and smaller fragments, facilitating their long-range transport to new environments. The degradation process also increases the microplastic surface area:volume ratio, facilitating adherence and transport of harmful organisms and chemicals (see *Microplastics as Transport Vectors* section below). Because microplastics can be easily ingested by many organisms, they bioaccumulate within organisms and the food web, leading to human exposure (Wu et al., 2022).

What Are Microplastics?

Microplastics are small plastic particles that are manufactured (*primary* microplastics) or generated through the degradation of manufactured products (*secondary* microplastics). As noted above, the chemical composition of microplastics vary greatly as do the size and shape. These differences have implications for the transit, fate, and persistence of microplastics in the environment (Hale et al., 2022; JC Prata et al., 2020; Wu et al., 2019).

Microplastics Definition

Microplastics are polymer particles <5 mm in one dimension

Primary microplastics are purposefully manufactured as:

- Microbeads/microspheres for abrasion (e.g., cosmetic and personal care products);
- Pellets (nurdles) for "feedstock" for plastics manufacturing;
- Particles for air-blasting technology and printer toner; and
- Films or resins (coatings for seeds or fertilizers).

Secondary microplastics are generated from the degradation of plastic products, such as:

- Packaging;
- Synthetic textiles;
- Rope; and
- Tires and brakes (including dust from braking, and recycled rubber granulate for athletic turf and playgrounds).

Size

Although the issue is not entirely settled, a 2008 international workshop achieved consensus among many in the research community to use 5 mm as the maximum cut-off for microplastics (da Costa and Duarte, 2020). In this report, CalSPEC adopted a modified version of the California State Water Resources Control Board (SWRCB) definition, to include particulates measuring no larger than 5 mm (see *Glossary*) and nanoplastics. Nanoplastics are generally considered to be <1µm (µm = micron or one one-thousandth of a millimeter) (Halle and Ghiglione, 2021). For context, microplastics can range from the size of a pencil eraser to a virus (Bar-On et al., 2020; Wu et al., 2019).

Understanding the Scale of Microplastics

pencil eraser = 5 mm
pencil tip = 1 mm
diameter of human hair = 180 µm
naked eyesight threshold = 40 µm
red blood cell = 7.5 µm
coronavirus = 0.1 µm

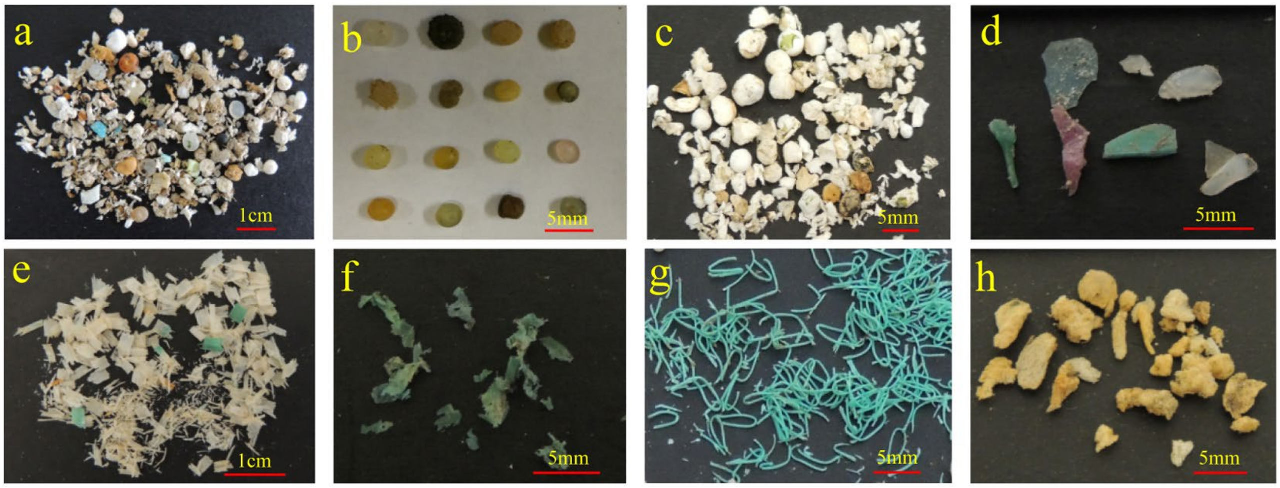
The size of a particle has implications for how it is transported as well as selection of prevention or mitigation strategies. For example, particles may be light enough to be carried by wind or small enough to pass through filtration systems or to be absorbed into the bloodstream.

Shape

Although terms used to describe microplastic shapes are still evolving, there are seven major categories: pellets, foams, fragments, flakes, films, fibers, and sponges (Figure 3) (Cowger et al., 2020b; Rocha-Santos et al., 2022; Zhou et al., 2018). Microplastic shape depends on whether the particles are produced from a primary or secondary source as well as their chemical composition.

Shape is important for at least three reasons. First, shape (along with size, composition, and surface charge) may affect toxicity. Based on extrapolations from earlier research on soot, asbestos, and dust particles, Wieland et al. (2022) assert that shape (regular, irregular, spherical, elongated, etc.) can influence toxicity to cells and tissues. For example, other types of rod-shaped fibers that become lodged in the lung can result in an ineffective immune response to clear the particles. This may lead to chronic inflammation and cancer. Second, shape affects a particle's ability to adsorb other chemicals or organisms that may introduce or increase harmful effects. Third, shape may inform choice of prevention and mitigation technologies such as filters (Athey and Erdle, 2021; Helm, 2017; Sutton et al., 2019).

Figure 3. Common Microplastic Shapes



Common types of microplastic shapes: a) mixed microplastics; b) pellets (beads); c) foams; d) fragments; e) flakes; f) films; g) fibers (fishing lines); h) sponges

Source: Zhou et al., 2018. [Reprinted from Geoderma, 322, Q. Zhou et al. (2018), pg. 201-208, *The Distribution and Morphology of Microplastics in Coastal Soils Adjacent to the Bohai Sea and the Yellow Sea,* with permission from Elsevier.

Formation of Microplastics

As described above, microplastics are classified as:

- **Primary microplastics**, manufactured *de novo* such as preproduction commercial feedstock to produce virgin plastic goods and abrasives for cleaning/cosmetic products; or
- **Secondary microplastics**, which are derived from the degradation of products composed of plastic.

The formation of secondary microplastics, which are more prevalent in the environment than primary microplastics, occurs through one or more of the following processes listed below. All processes are gradual, and repeated exposure makes microplastics further susceptible to fragmentation on a nanoscale (Magalhães et al., 2020; Prata et al., 2020; Wu et al., 2019).

- **Physical processes** include actions such as abrasion against natural and manmade objects in aquatic and terrestrial settings through movement of air (wind) and water (waves, currents).
- **Chemical processes** can weaken or break polymer bonds. Heat (thermo-degradation/thermo-oxidation), water (hydrolysis), and ultraviolet radiation (photo-degradation) are examples of the chemical process.
- **Biodegradation processes** are caused by microorganisms through the course of digestion or through ultraviolet exposure from sunlight.

Microplastics Transport and Conveyance

Sorption Explained

- Sorption: one substance becomes attached to another via chemical and physical processes
    - Absorption: one substance is absorbed or penetrates another substance
    - Adsorption: one substance adheres to the surface of another substance
- Desorption: the release of one substance from the surface of another

The introduction of microplastics to the environment may occur during any stage of the plastics life cycle, though mostly during disposal (Stage 4).

Managed disposal of plastic products includes landfill placement, incineration, and recycling. It is now understood that landfill and incineration of plastic products ultimately produces microplastics, which may or may not remain at the disposal site. The percentage of plastics deposited into landfills varies worldwide and ranges from 22% to 65% of landfill across countries. Globally, about 25% of plastics are incinerated to avoid landfill, though this process generates ash output, which contains microplastics. When ash is transferred to landfill, it may disperse microplastics through air and water (Kumar et al., 2021; McInturf and Savoca, 2021). Wastewater treatment provides another managed disposal process wherein some, but not all, microfibers or particulates are diverted through the filtration process into sludge output, which is subsequently incinerated, landfilled, or processed into biosolids for land application. Recycling is the least used managed disposal method. Despite widespread support for recycling, the US Environmental Protection Agency estimates that 8.5% of plastic is recycled in the US (EPA, 2022c).

Microplastics transport may be intermittently punctuated by periods of repose or transient storage, regardless of whether disposal is managed or unmanaged (Figure 4). Transport may occur via wind, storm runoff, rivers, wastewater, evaporation, rain, and ocean currents. Final deposition is frequently unknown due to the prolonged process that changes microplastics composition through physical, chemical, and biodegradation processes, as well as the lack of comprehensive studies measuring occurrence in locales globally. Figure 4 depicts sources of microplastics, the manner of transport throughout the environment, and the deposit areas — microplastic "sinks" — where microplastics may settle temporarily or permanently.

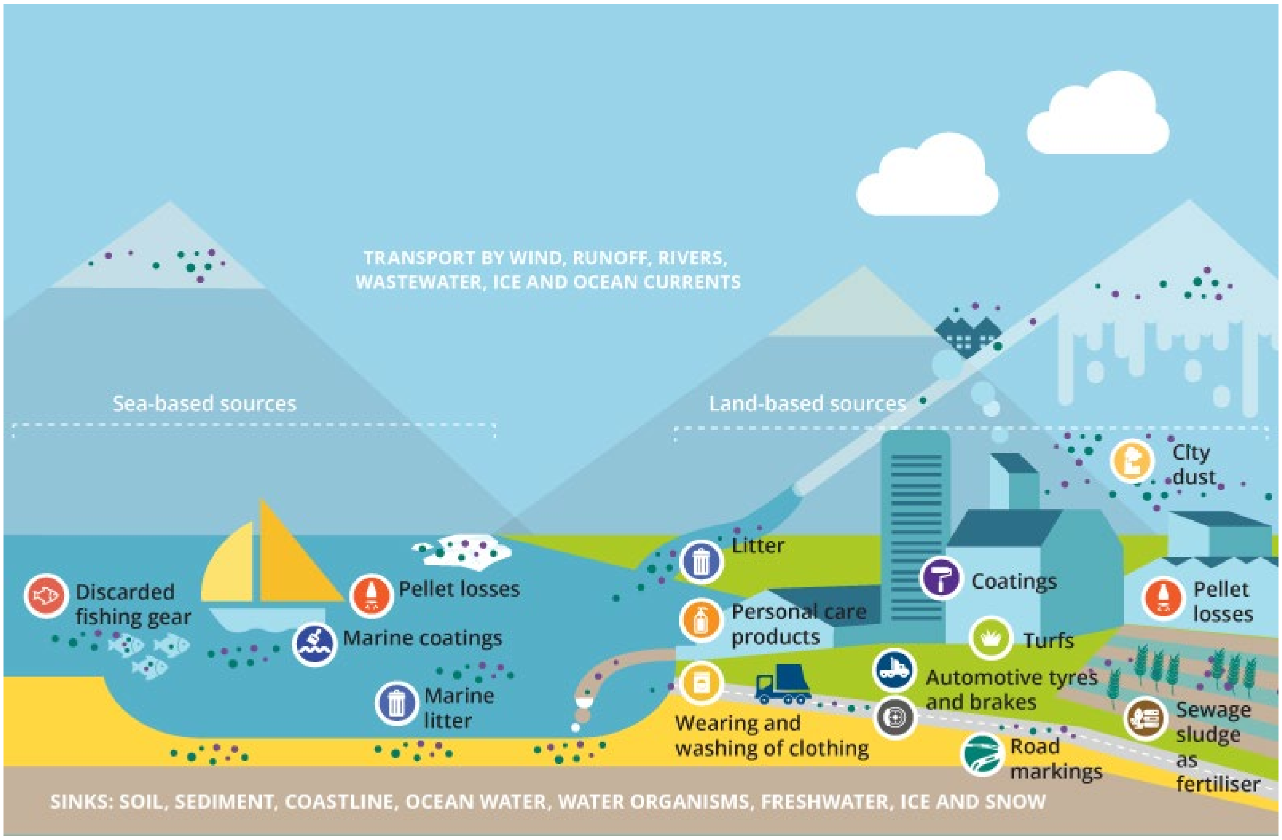
Unmanaged disposal occurs through littering and open dumping or otherwise unintended transport of plastic products from managed sources (e.g., spills of pellets during transport to manufacturing sites, microbeads from personal care products; microfibers from laundry, tire and brake dust, and packaging litter). These plastics also eventually degrade into secondary microplastics with the capacity to disperse throughout the environment.

Microplastics as Transport Vectors

In addition to concerns about the potential hazards from microplastics leaching polymers and chemical additives (CDC, 2022a,b; Frias, 2020; Pelmatti et al., 2020; Santos et al., 2020), scientists have begun to study microplastics as vectors that serve as conveyance vehicles for other chemical and biologic contaminants. These other products can adhere to microplastics in two different ways: absorption and adsorption; they are released through a process called desorption.

How and when sorption (adherence of a new substance to microplastic) and desorption (release of substance from microplastic) occurs has different implications for toxicity. Several studies report aquatic microplastic sorption of toxic compounds such as pesticides, trace metals (e.g., lead, arsenic), and PCBs (Karapanagioti et al., 2020; Santos et al., 2020). Other studies report the formation of biofilms created by local microbial organisms using marine microplastic as a habitat.

Figure 4. Microplastics Distribution across the Environment



Source: Illustration by the Collaborating Centre on Sustainable Consumption and Production for the European Topic Centre on Circular Economy and Resource Use and the EEA (Saskia et al., 2022).

These films change microplastic density and buoyancy, which affects transport and fate of the plastic, potentially introducing the microplastic and "hitchhiking" microbes to new environments (Baptista Neto et al., 2020; Halsband, 2020). Some scientists posit that biofilms support colonies that are consumed as food by higher order organisms (Baptista Neto et al., 2020). Other studies show microplastic adsorption of pharmaceuticals (antibiotics) in marine and fresh water (Lan, 2020).

Occurrence of Microplastics in the Environment

Despite the fact that microplastics have been detected across all environmental compartments and have been observed in the most remote areas of the environment (e.g., Artic ice and deep-sea sediment) (Gong and Xie, 2020; Eerkes-Medrano et al., 2015), the exact prevalence of microplastics in the environment is unknown due to several factors including:

1. Lack of standardized measurement and analytical methods (see "Challenges with Measuring Microplastics"). Because there are different definitions of microplastics, studies that include a wider range of particle sizes in their analysis (such as nanoplastics or plastic particles

larger than 5 mm) may find higher concentrations of microplastics than studies that use more limited ranges.

2. Uneven distribution of microplastics in the environment due to human activity (e.g., socioeconomic practices and policies) and environmental factors (e.g., waves, currents, tides, wind directions, river hydrodynamics, water density, and weather) (Shahul Hamid et al., 2018). Because of these factors, the concentration and character of microplastics can be highly variable spatially and temporally in the environment.

Global Occurrence of Microplastics

Research about microplastics occurrence is most often siloed according to the environmental compartment (water, soil, air, and living organisms [biota]), shape (bead, fiber, fragment), or chemical composition. *Thus, CalSPEC is unable to provide a comprehensive accounting of microplastics prevalence.* Widely cited research from the International Union for Conservation of Nature estimates that about two-thirds of microplastics in the global marine environment are from fragmentation of virgin plastics (tires, synthetic textiles, city dust, road markings, marine coatings, etc.) (Boucher and Friot, 2017). Another commonly repeated estimate: microplastics annually released to land are 4 to 23 times greater than microplastics released to oceans (Horton et al., 2017).

The following sections provide a broad overview of peer-reviewed study findings about the occurrence of microplastics in humans as well as occurrence in the four primary environmental compartments. Note that estimates of microplastic occurrence will continue to change as the field develops.

Overview of Microplastics Measurement Processes

Measuring microplastics to identify the presence, size, shape, density, and polymer composition involves:

- Sampling the environmental compartment (such as air, water, soil, or biota) in a geographic region;
- Separating or extracting microplastics from the sample; and
- Identifying microplastics (visually and/or chemically) using a wide variety of tools such as filtration and visual review, microscopy, mass spectrometry, or infrared or Ramen spectroscopy (da Costa and Duarte, 2020; Hidalgo-Ruz et al., 2012).

Analytical approaches to quantify microplastics can be either particle-based or mass-based, which result in different units of measurement (e.g., particle counts versus grams or liters) used to describe the presence (Hidalgo-Ruz et al., 2012).

Challenges with Measuring Microplastics

While standard methods for sample collection, laboratory analysis, and quality assurance are being developed by research groups (Cowger et al., 2020a; see *Chapter 4: Microplastics Policies* for government mandates on microplastics research), these standards methods are not yet commonly utilized in published research. Until standard methods are adopted by the research community, heterogeneous methods will continue to hamper the comparability of the research and inhibit progress in identifying (the severity of) problems (Cowger et al., 2020a).

Another key issue of measurement concerns is quality control methods used during the testing process. High-quality studies use and explain the rigorous quality control measures to prevent uncontrolled exposure or cross-contamination during sampling and measurement, although contamination is usually not completely eliminated. Without steps to assess background contamination, research may produce inaccurate results leading to a misunderstanding of the relationship between exposure to microplastics and potential effects (de Rujiter et al., 2020).

Microplastics Occurrence in Humans

Routes of human microplastic exposure include inhalation, digestion, and dermal contact (e.g., hair follicles, sweat glands, injured skin). Due to measurement limitations, scientists suspect that studies undercount particles in human tissue, which has implications for understanding effects at the chemical, cellular, and tissue levels (Huang et al., 2020; Stapleton, 2021; Wu et al., 2022).

The Kutralam-Muniasamy et al. (2022) review found 20 biomonitoring studies about abundance of microplastics in 16 different types of human biological samples (all published since 2019 despite no publication year restrictions) with most studies focused on a single tissue type. Several studies in the review reported a *correlation* between higher concentrations of microplastics among people with disease as compared with healthy people. Authors note that more study is required to determine whether microplastics cause disease or disease inhibits removal of microplastics.

Highlights from Kutralam-Muniasamy et al.'s (2022) review:

- Fibers and fragments were most often recorded, while smaller numbers of films, sheets, and spheres were found.
- Size ranged from ≥700 nm to 5 mm with smaller particles in breast milk, lungs, and placenta (usually in the range of 5 to 50 μm) and larger particles found on skin/hair or in feces.
- The polymers reported in Table 1 were identified in at least one type of biological sample among the 20 studies.

Table 2 summarizes examples of estimated overall annual intake of microplastics by humans and concentrations of microplastics in different biological sample types. (*Note*: CalSPEC used the Q. Zhang et al. [2020] estimate of 422 particles consumed by humans/day when converting animal exposure study results to human exposure in *Chapter 3*.)

Table 2. Examples of Microplastics Occurrence in Humans

Biological Sample Type	Examples of Occurrence of Microplastics	Microplastic Particle Size
Overall annual intake[a]	A person might ingest between 39,000 and 52,000 microplastic particles per year through food alone; estimates increased to 74,000–121,000 when accounting for air inhalation (with higher levels of contamination in indoor vs. outdoor environments).	Not reported
	Water intake by only bottled sources is estimated to account for an additional ingestion of 90,000 microplastic particles annually (Cox et al., 2019). Water intake by only tap water is estimated to account for ingestion of 4,000 particles annually (Cox et al., 2019).	Not reported
Daily intake[b]	In studies of exposed rodent groups, daily microplastics intake is approximately 7–70,000 microplastics particles. Converting these results to human exposure, the estimated daily intake for humans is around 422 particles per day.	5–150 µm
	For smaller microplastics sizes, the same study also found that the range of daily exposure concentrations was around 7×10^{6} to 9.1×10^{10}. This could be higher than estimated human exposure concentrations but estimates will continue to change as the field develops.	0.1–0.5 µm
Blood[c]	Average concentration of 1 microgram per milliliter	≥700 nm
Breast milk[c]	Average concentration of 0–2.72 microplastics per gram	2–12 µm
Colon[c]	Average concentration of 28.1 microplastics per gram	0.8–1.6 mm with an average of 1.1 mm
Feces[c]	Feces material was most often studied (30%) and an average concentration of 1–138.9 microplastics per gram was identified.	50–500 µm; 20–800 µm; <50 to >300 µm; 40.2–4,812.9 µm
Hair[c]	Average accumulation of >3.5 microplastics per individual per day	<100 to >500 µm
Hand[c]	Average accumulation of 2.1 microplastics per individual per day	Not reported
Liver[c]	Average accumulation of 4.6 microplastics per gram	4–30 µm
Lung[c]	Average concentration of 1.17–2.84 microplastics per gram	5.5–18 µm; 12– 2,475 µm
Bronchoalveolar lavage fluid (BALF)[c]	Average concentration of 9.18 microplastics per milliliter	Avg 1.73 ±0.15 mm; >20 µm
Placenta/ meconium[c]	Average concentration of 3 microplastics per gram	5–10 µm (placenta); >50 µm (placenta and meconium)
Saliva[c]	Average accumulation of 0.33 microplastics per individual per day	Not reported
Skin[c]	Average accumulation 2.02 microplastics per individual per day	Not reported

Source: CalSPEC, 2023, based on (a) Cox et al. (2019); (b) Q. Zhang et al. (2020); (c) Kutralam-Muniasamy et al., 2022.

Microplastics Occurrence in Food

Microplastics have been studied in various foods because a major entry point of microplastics into humans is the ingestion of contaminated food. Table 3 shows estimated of annual human intake of microplastics from food and examples of microplastics occurrence in food.

Table 3. Examples of Microplastics Occurrence in Food

Food Type	Examples of Occurrence of Microplastics	Microplastic Particle Size
Estimated annual human intake from food[a]	In a review of 77 studies on microplastics in various food samples, the estimated the maximum annual human intake of microplastics from beverages, condiments, honey, meat, seafood, and vegetables was approximately 140,000–155,000 microplastic particles per year.	0.1 µm–5 mm
Meat and vegetables[a,b,c]	A review of studies on microplastics in food samples by found that most studies focused on fish and marine mammals (mainly sea fish, but also crustaceans, mollusks, canned fish). The review identified one study on chickens but did not find any studies measuring microplastics in meat such as pork, goat, or sheep.	<5 mm
	Another review reported an average abundance of 4–19 particles of microplastics per kilogram (kg) of meat across 3 studies, and an average abundance of 900 to 3,000 particles of microplastics per kilogram (kg) of vegetables sampled across 3 studies.*	0.1 µm–5 mm
Seafood[b,d,e,f,g]	A study of shellfish found 10–100 microplastics per gram in oysters and mussels.	300–5,000 µm
	Farmed mussels were found to have almost twice as many microplastics particles as compared with wild mussels (180 vs. 100 particles per mussel, respectively).	>0.8 µm
	In mollusks, microplastics ranged from 0 to 10.5 microplastics per gram, in crustaceans, microplastics ranged from 0.1 to 8.6 microplastics per gram, and in fish, microplastics ranged from 0 to 2.9 microplastics per gram.	<5 mm
Salt[g]	A meta-analysis found that microplastic contamination varied significantly based on origin. Sea salt ranged from 0 to 1,674 microplastics per kilogram; lake salt ranged from 8 to 462 microplastics per kilogram; and rock and well salt ranged from 0 to 204 microplastics per kilogram.	<5 mm
	Conesa and Iñiguez (2020) concluded that levels of microplastics in sugar were comparable to microplastic levels found in salt.	<5 mm
Drinks[a,b]	A review of studies about microplastics in food reported a range of 0 to 5,680 microplastic particles per kilogram in beverages.	.1 µm–5 mm
	Microplastics have been detected in beverages such as apple juice, wine, milk, and beer ranging from 2 to 254 microplastic particles per liter.	<5 mm

Source: CalSPEC, 2023 based on a) Bai et al., 2022; b) Conesa and Iñiguez, 2020; c) Conti et al., 2020; d) Gautum et al. (2020); e) Leslie et al., 2017; f) Mathalon and Hill, 2014; g) Danopoulos et al., 2020c.

**Note:* Study findings on fruits and vegetables are highly variable. Another study on fruits and vegetables found a much greater abundance of very small microplastics (<10 µm in size) ranging from 52,000 to 233,000 per gram depending on type and source of the food sample. Fruits such as apples showed the highest presence of microplastics compared to vegetables.

Microplastics Occurrence in Flora and Fauna (Biota)

The presence of microplastics in freshwater, marine, and terrestrial environments prompted investigations about the potential effects of microplastics in flora and fauna living in those environments (Gautam et al., 2020). Biota studies primarily focus on marine species (such as mussels, fish, zooplankton, seagrass, and coral), but animal and plant species in freshwater and soil environments are now receiving more attention (Allen et al., 2022) (Table 4). Microplastics have been detected in a significant portion of biota that have been studied.

Table 4. Examples of Microplastics Occurrence in Flora and Fauna (Biota)

Biota Type	Examples of Occurrence of Microplastics
Animal species[a]	Microplastics have been detected in animals such as:
	• Zooplankton • Fish (such as catfish, anchovies, sardines, zebrafish) • Oysters • Mussels • Crabs • Tortoises • Earthworms • Mice • Gastropods (such as snails) • Springtails • Chickens (through feces samples)
	In studies among 800 animal species, 247 species were contaminated with plastics, and 220 species were found with ingested plastic particles.
	In studies of edible freshwater fish in South America, microplastics debris and microfibers were present in the digestive tract of 83% of fish sampled.
Plant species[a,b,c,d]	Microplastics have been detected in plants such as:
	• Freshwater algae • Seagrass • Coral • Garden Cress • Duckweed • Agricultural plants (e.g., tomato, cucumbers, carrots, lettuce, radish)
	Most studies on plants focus on the effects of microplastics exposure on plants, which vary across plant species.

Source: CalSPEC, 2023, based on (a) Gautam et al., 2020; (b) Allen et al., 2022; (c) Campanale et al., 2022; (d) Mendes, 2021.

Microplastics Occurrence in Water (Aquatic Compartment)

Most published microplastics research focuses on marine environments, with a significant portion concentrating on microplastics in surface and subsurface waters in oceans and seas (Akdogan and Guven, 2019). Table 5 shows examples of the occurrence of microplastics in different aquatic environments.

Table 5. Examples of Microplastics Occurrence in Water

Aquatic Source	Examples of Occurrence of Microplastics	Microplastic Particle Size
Marine[a,b]	Samples from sea surfaces contained an average range of 0.022 to 8,654 microplastics items per cubic meter.	1 µm–5 mm
	Sea sediment samples contained substantially greater amounts of microplastics ranging from 185 to 80,000 microplastics items per cubic meter (m^3).	1 µm–5 mm
	A modeling study estimated that world's oceans contain 5.25 trillion plastic particles. Of those, 4.85 trillion are microplastics ranging from 0.33 to 4.75 mm in size.	0.33–4.75mm
Freshwater[c,d]	1 particle per 100 cubic meters (m^3) to 1 million particles per cubic meter (m^3); 100,000 particles per cubic meter along shorelines (various locations in North America, Europe, Asia, and Australia)	<5 mm
	The Province of Ontario's Ministry of Environment and Climate Change in Canada found significant quantities of microplastics in water samples from Lake Erie and Lake Ontario, with microbeads comprising 14% of total litter. (Subsequently Illinois banned microbeads in 2014, by passing SB 2727 Microbead Ban; see *Chapter 4: Microplastics Policies*).	<5 mm

Drinking water[e]	European samples of tap water ranged from 0 to 628 particles per liter; samples from bottled water ranged from 0 to 4,889 particles per liter.	1–100 µm
Wastewater[f,g,h]	Estimated daily wastewater discharges of microplastics range from 50,000 up to nearly 15 million particles per day based on samples from US wastewater treatment plants (WWTP).	125 µm–5 mm
	A study in 3 secondary US WWTPs identified an average of 4.8 microplastics per liter of effluent. Although these particles are removed from the water cycle, they may be reintroduced to the ecosystem through sewage sludge incineration, fertilizer, or landfilling.	60–418 µm

Source: CalSPEC, 2023 based on (a) Hidalgo-Ruz et al., 2012; (b) Eriksen et al., 2014; (c) Eerkes-Medrano et al., 2015; (d) Government of Ontario, 2021; (e) Danopoulos et al., 2020a; (f) Mason et al. 2020; (g) Khan et al., 2020; Conley et al., 2019.

Microplastics Occurrence in Soil (Terrestrial Compartment)

Soil is considered a significant sink for accumulating microplastics because soil is a major transporter of microplastic contaminants to the aquatic environment; it is also one of the direct pathways of microplastics into the food chain (Allen et al., 2022; Kim et al., 2020; J. Li et al., 2020). However, it is one of the most difficult compartments to analyze for microplastics abundance because of the presence of confounding organic matter content and complex composition of soil (Allen et al., 2022). A commonly repeated estimate from a single source is that microplastics annually released to land are 4 to 23 times greater than microplastics released to oceans (Horton et al., 2017). Table 6 provides examples of the occurrence of microplastics in different terrestrial environments.

Table 6. Examples of Microplastics Occurrence in Soil

Terrestrial Source	Examples of Occurrence of Microplastics	Microplastic Particle Size
Agricultural fields[a,b,c]	A study across agricultural fields in China reported up to 1,075 microplastic particles per kilogram of dry soil.	<5 mm
	Another study on vegetable fields in China found an average abundance of 78 microplastic particles per kilogram in shallow soil and 62.5 microplastic particles per kilogram in deep soil.	20 µm–5 mm
	In European farmlands, estimates range between 63,000 to 430,000 metric tons of microplastics are added to the farmlands annually via sewage sludge (fertilizer).	Not reported
Suburban soil and road sediment[a,d,e]	Studies of suburban soil and road sediment show that 320 to 12,560 microplastics particles per kilogram were measured in various locales, with greater amounts of microplastics present in soil adjacent to suburban roads.	0.02–5 mm
	Up to 7% of topsoil weight around roads and industrial areas in Australia was from microplastics.	>1 mm

Source: CalSPEC, 2023 based on (a) Peller et al., 2020; (b) Y. Huang, et al., 2020; (c) Liu et al., 2018; (d) Chen et al., 2020; (e) Gautam et al., 2020.

Microplastics Occurrence in the Air (Atmospheric Compartment)

Airborne microplastic appears to be the least studied compartment (Allen et al., 2022). Because air is contaminated continuously by particles released by building materials, furniture, clothing, and lab equipment, contamination of air samples is a concern when measuring microplastics (Prata et al., 2020). The few studies conducted in specific regions or cities in North America, Europe, and Asia had short periods of monitoring, making estimates of concentration highly uncertain. Studies in several European and Asian countries found that indoor environments generally had higher concentrations of microplastics than outdoor environments, although the concentration of microplastics in indoor air samples depended heavily on where the sample was collected (Prata et al., 2020). Researchers postulate that the higher indoor concentrations might be due to the closed environment that traps and recirculates microplastics generated from common household products (e.g., carpeting, clothing, bedding, cleaning products, kitchenware) (Kacprzak and Tijing, 2022). Additionally, study findings suggest that the primary sources of atmospheric particles in the western US are roads, the ocean, and agricultural soil dust (Brahney et al., 2021). Table 7 shows examples of microplastics occurrence in indoor and outdoor air samples.

Table 7. Examples of Microplastics Occurrence in Air

Air Sample Type	Examples of Occurrence of Microplastics	Microplastic Particle Size
Indoor air[a,b]	Studies conducted in China, Turkey, Iran, France, Denmark, and Germany found that indoor samples contained a range of 0.4 to 59.4 particles per cubic meter (Prata et al., 2020).	0.45–5 mm
	A study conducted in coastal areas of Southern California found that indoor samples contained an average range of 3.3 to 12.6 particles per cubic meter (Prata et al., 2020).	20 µm–5 mm
Outdoor air[a,b,c,d]	Studies conducted in China, Turkey, Iran, France, Denmark, and Germany found that the concentration of microplastics in outdoor samples ranged from 0 to 1.5 particles per cubic meter (Prata et al., 2020).	0.45–5 mm
	A study conducted in coastal areas of Southern California found that indoor samples contained an average range of 0.6 to 5.6 particles per cubic meter (Prata et al., 2020).	20 µm–5 mm
	Another of review of studies in European, Middle Eastern, and Asian cities identified concentrations of 1 to 5,700 microplastics particles per cubic meter in outdoor air (Prata et al., 2020).	1 µm–5 mm
	A study conducted in protected areas of the United States (such as national parks and national wilderness areas) found that microplastics were present in 98% of samples of wet and dry atmospheric deposition. Deposition rates averaged 132 plastic particles per square meter per day (amounts to >1,000 metric tons of plastic deposition annually).	4–188 µm (particles); 20 µm–3 mm (fibers)

Source: CalSPEC, 2023, based on (a) Prata et al., 2020; (b) Gaston et al., 2020; (c) Allen et al., 2022; (d) Y. Zhang et al., 2020.

Microplastics Explained Chapter Summary

Continued global reliance on plastics has led to concerns of microplastic pollution in the environment. Primary microplastics (purposefully manufactured) and secondary microplastics (degraded plastic products) are transported through the environment by air/wind, water, soil, and human activity; they have been detected everywhere they have been studied including exceptionally remote areas such as the deep sea and the Arctic. Challenges to microplastics research include inconsistent and uncoordinated analytic methods and contamination introduced during the research process (such as through lab equipment, tools, or clothing). Additionally, the concentration and character of microplastics can be highly variable spatially and temporally in the environment making accurate measurement challenging.

Although progress has been made in understanding the sources, fate, transport, persistence, and occurrence of microplastics in the environment, the exact prevalence of microplastics in the environment and the environmental and health effects of microplastics remain unclear. Subsequent chapters of this report explore in more depth the health effects of microplastics and microplastics laws at various levels of government.

CHAPTER 3: HEALTH EFFECTS OF MICROPLASTICS

What is known about this topic? Microplastics are persistent environmental contaminants, and the production and release of microplastics have been increasing over time. There are documented human exposures, and multiple studies have been conducted in animals evaluating a range of adverse health outcomes.

What this report adds: CalSPEC performed a rapid systematic review (rapid review) of specific health outcomes for two organ systems (reproductive and digestive) and a narrative review of respiratory system outcomes. There were no human studies. Of the three classifications of hazards to human health possible based on mammalian animal data (presumed, suspected, and not classifiable as a hazard), CalSPEC found that microplastics are suspected to promote deleterious human health effects in the reproductive and digestive systems. Although the respiratory tract data were not evaluated as rigorously, CalSPEC concludes that respiratory harms from microplastics could also be suspected.

What are the implications for research and policy? These findings can be used to prioritize research on other human health endpoints that might be adversely affected by microplastics. Given that microplastics are persistent in the environment and living systems, accumulate in living organisms, and are suspected to cause harm to human digestive, reproductive, and respiratory systems, research should focus on identifying strategies for reducing and mitigating exposures to microplastics. At the same time, regulators should consider suspected human harm in shaping policy around the production, distribution, and disposal of microplastics.

Introduction

This report seeks to answer the question "What are the human health effects from microplastics exposure?" CalSPEC found no systematic reviews assessing the quality or strength of the evidence on the human or animal health effects of microplastics. Therefore, CalSPEC conducted a rapid systematic review (rapid review) following well-accepted procedures (Garritty et al., 2021; NTP, 2019; Woodruff & Sutton, 2011). CalSPEC used a rapid review rather than a narrative literature review based on the recommendation of the National Academy of Sciences, Engineering, and Medicine (NASEM) to use systematic methods when evaluating environmental contaminants to inform policy and decision-making (NASEM, 2017, 2018, 2022; NRC, 2014).

This rapid review focuses on studies that evaluate exposure to microplastics as defined in *Chapter 1: Introduction* and in the accompanying protocol (see Appendix A). The review does not cover chemicals that can degrade from plastics, which include many different types of chemicals such as phthalates, bisphenols, polyaromatic hydrocarbons (PAHs), and flame retardants. Many of these chemicals are known or presumed to be toxic or carcinogenic (ACOG, 2013; ACOG, 2021; NASEM, 2017; OEHHA, 2021). Additionally, many of these chemical additives can interfere with hormone systems making them endocrine disrupters (La Merrill et al., 2020). These represent possible additional health hazards from microplastics but are not considered in this report, meaning that the conclusions from this work likely underestimate the true harms from microplastics exposure.

The Difference Between Systematic Reviews and Rapid Reviews

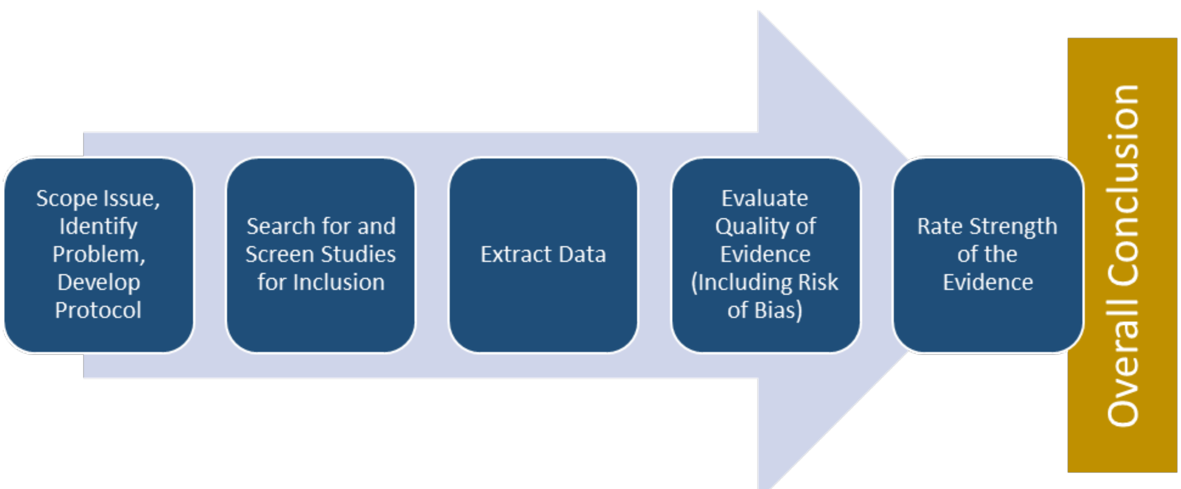
Systematic review: a type of review that synthesizes all available evidence relevant to a specific research question. Systematic reviews provide an overview of what is known and what is not known about a topic. Their main advantages over less formal "narrative" reviews are comprehensiveness, transparency, consistency, reproducibility, and less susceptibility to bias.

Rapid systematic review: a type of systematic review that omits certain methodological steps to significantly accelerate the process of performing a traditional systematic review when quality systematic reviews are not available to answer a time-sensitive question (Garritty et al., 2021).

Methods

In performing this rapid review, CalSPEC used prespecified search terms and study selection criteria as well as standard methods for evaluating study quality, assessing strength of evidence, and analyzing study results. The detailed methods are described in the protocol in Appendix A.

Figure 5. Steps Taken for this Rapid Review



Source: CalSPEC, 2023.

Study Screening and Selection

CalSPEC performed a comprehensive search with a medical librarian to identify any human or animal studies that examined any exposure to microplastics (particles less than 5 mm [5,000 microns]) and any adverse health outcomes. CalSPEC did not restrict the search by publication date and included any relevant study published through July 12, 2022 (literature search date).

CalSPEC found no human studies that met the eligibility criteria. Therefore, this rapid review focused on mammalian rodent studies, which are routinely used by regulatory agencies[10] to identify potential human health harms as they mimic human health effects.

CalSPEC used the US Environmental Protection Agency (US EPA) and California law definitions of adverse health outcomes, which include biochemical changes, functional impairments, and pathological lesions affecting the performance of the whole organism or reducing an organism's ability to respond to environmental challenges (State of California, 2011; EPA, 2022b).

To rapidly identify and evaluate evidence relevant to humans, CalSPEC focused on the digestive, reproductive, and respiratory systems. CalSPEC chose these three organ systems because:

- *The digestive system* is the first point of contact for drinking and eating exposures.
- *The reproductive system* may be particularly sensitive to environmental insults (EPA, 1996), and this outcome is of policy interest to regulatory agencies including the California Environmental Protection Agency (CalEPA).
- *The respiratory system* accounts for direct airborne microplastics exposure.

For inclusion in this rapid review, studies were required to meet the following criteria (reflecting common pathways of human exposure):

- Animals repeatedly exposed to microplastics (i.e., sequential applications to simulate chronic exposure and to assess potential dose-response relationships);
- Animals exposed via food or water for digestive and reproductive studies; and
- Animals exposed by direct application to the nasal passages or trachea for respiratory studies.

CalSPEC took a staged approach to evaluating these studies (Table 8 and Appendices cited below). In brief, CalSPEC applied the most rigorous evaluation to digestive and reproductive system studies. In contrast, data from respiratory system studies were only extracted and summarized.

Table 8. CalSPEC Staged Evaluation Approach

Levels of Rigor	System	Explanation
High	Digestive system	CalSPEC evaluated the quality and strength of outcomes for apical endpoints and six biological changes.
	Reproductive system	CalSPEC evaluated the quality and strength of outcomes for apical endpoints and one biological change. The same level of rigor used for the digestive system is applied, but for fewer endpoints.
Low	Respiratory system	CalSPEC did not evaluate the quality and strength of the outcomes.

Outcomes of Interest

CalSPEC prioritized outcomes where data relevant to human health was most available and would be of higher confidence. For the *digestive system* and *reproductive system* outcome studies, CalSPEC considered both apical endpoints and biological changes, focusing on endpoints that are reasonably well established in evaluations of health hazards:

- **Apical endpoints** are observable outcomes (i.e., death, cancer, impaired reproduction, and other clinical signs or pathologic states) in a whole organism that are indicative of a disease that can result from exposure to a toxicant.
- **Biological changes** in this rapid review are categorized according to the key characteristics of cancer-causing agents (carcinogens) (Smith Martyn et al., 2016) and key characteristics of reproductive toxicants (Arzuaga et al., 2019; Luderer et al., 2019). The key characteristics, described in Table 9, are mechanisms or biological pathways that are known to be linked to systemic or observable endpoints, like cancer or reproductive toxicity.

Table 9. Key Characteristics of Carcinogens & Reproductive Toxicants

Key Characteristic of Carcinogens	Key Characteristic of Reproductive Toxicants (Male)	Key Characteristic of Reproductive Toxicants (Female)	Definition
Electrophilic or metabolically activated	–	–	Forms addition products, often referred to as adducts, with DNA and other molecules (RNA, lipids, and proteins).
Genotoxic	Is genotoxic	Chemical or metabolite is genotoxic	Causes DNA damage and/or mutation
Alters DNA repair or causes genomic instability	–	–	Alters the repair of DNA damage or disrupts the stability of the genome.
Induces epigenetic alterations	Induces epigenetic alterations	Induces epigenetic alterations	Impacts gene expression without affecting the DNA sequence
Induces oxidative stress	Induces oxidative stress	Induces oxidative stress	Disrupts the balance of production and detoxification of reactive oxygen species
Induces chronic inflammation	Induces inflammation	–	Causes a prolonged inflammatory response
Is immunosuppressive	–	Alters immune function	Suppresses immune surveillance of cancer cells; alters immune system function
Modulates receptor-mediated effects	**Alters production and levels of reproductive hormones OR alters hormone receptor levels/ functions**	**Alters hormone receptor signaling; alters reproductive hormone production, secretion, or metabolism**	Changes processes, such as hormone actions, that are controlled through receptors
Causes immortalization	–	–	Increases the life span of tumor cells so they replicate indefinitely

Key Characteristic of Carcinogens	Key Characteristic of Reproductive Toxicants (Male)	Key Characteristic of Reproductive Toxicants (Female)	Definition
Alters cell proliferation, cell death, or nutrient supply	Alters germ cell development, function, or death OR alters somatic cell development, functions, or death	Alters survival, proliferation, cell death, or metabolic pathways	Promotes the growth of tumor cells and helps them evade death; alters the growth, function, or development of germ cells or somatic cells

Source: CalSPEC, 2023, based on (Arzuaga et al., 2019; Luderer et al., 2019; Smith Martyn et al., 2016)

Notes: Key characteristics in grey font were not evaluated as part of this rapid review. Additional key characteristics that have been identified for female reproductive toxicity include causes mitochondrial dysfunction, alters cell signal transduction, alters direct cell-cell interactions, and alters microtubules and associated structures.

Table 10 summarizes the study outcomes evaluated for the three physiological systems covered in this rapid review. This review does not necessarily include all the outcomes that were evaluated in the studies themselves.

Table 10. Overview of Adverse Health Outcomes Extracted from Studies in this CalSPEC Review

Outcomes for which quality and strength of evidence were evaluated	
Digestive	• **Apical endpoints** (e.g., colonic length) • **Key characteristics of carcinogens** (chronic inflammation; oxidative stress; immunosuppressive effects; cell proliferation; receptor mediated effects)
Reproductive	• **Apical endpoints** (e.g., sperm-related outcomes) • **Key characteristics of reproductive toxicants** (alterations in reproductive hormones)
Outcomes for which quality and strength of the evidence were not evaluated	
Digestive	• **Key characteristics of carcinogens** (epigenetic alterations, effects on DNA repair, or genomic instability)
Reproductive	• **Apical endpoints** (e.g., body weight) • **Key characteristics of reproductive toxicants** (oxidative stress; epigenetic alterations; genotoxicity. *Male*: inflammation, *Female:* alterations in immune function; *Male:* changes in germ or somatic cells, *Female:* altered survival, proliferation, cell death, or metabolic pathways) • **Other** (e.g., offspring survival)
Respiratory	• **Apical endpoints** (e.g., lung injury) • **Biological changes** (e.g., changes to gene expression)

Source: CalSPEC, 2023.

Note: More detail on the outcomes can be found in Tables 11–13 and Appendices B.2 and B.3.

Evaluating the Quality & Strength of the Evidence

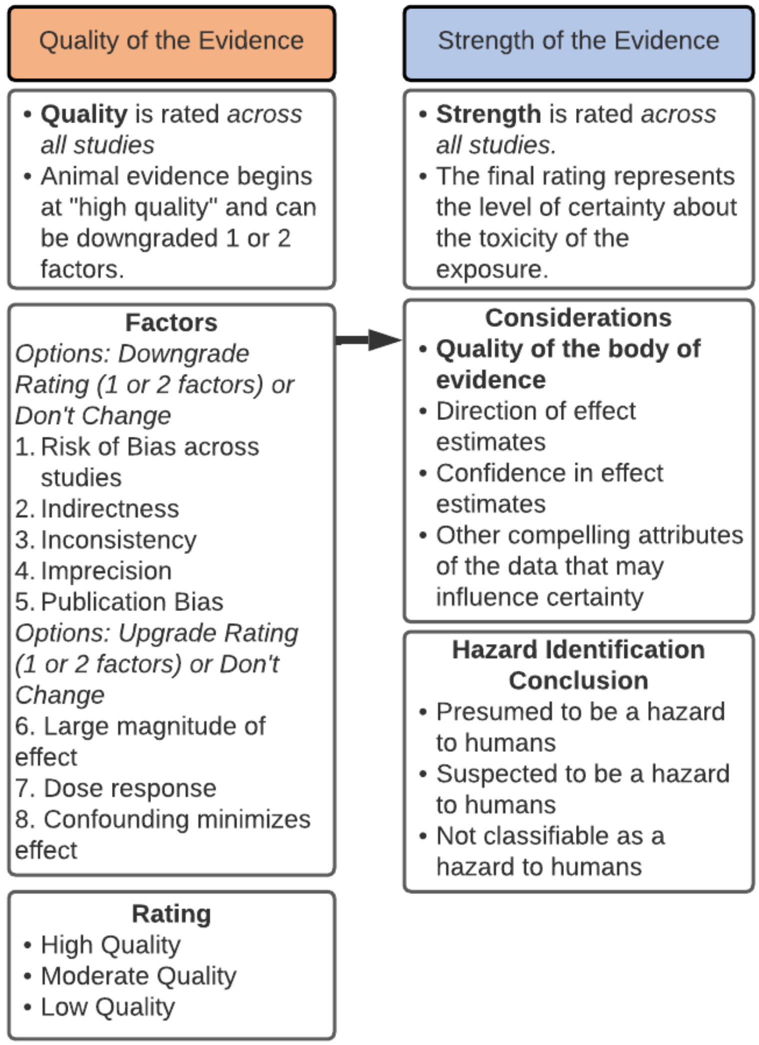
CalSPEC assessed the quality and strength of evidence *across* studies (Figure 6). After identifying the studies for inclusion and extracting relevant study data and information, the quality rating of high, moderate, or low was assigned based on consideration of the following: risk of bias, indirectness, inconsistency, imprecision, publication bias, magnitude of effects, dose response, and the extent to which controlling for potential confounders reduced any observed associations.

Next, a strength of evidence rating was assessed *across* studies based on: 1) quality of the body of evidence (i.e., the rating from the previous step); 2) direction of effect; 3) confidence in effect; and 4) other compelling attributes of the data that may influence certainty.

Following the strength of evidence assessment, CalSPEC assigned an overall hazard identification conclusion. With human studies, there are five possible hazard identification statements that can be assigned. As CalSPEC did not identify any human studies included in the rapid review, only one of the following three statements could be assigned based on the quality and strength of the evidence from animal studies regarding the human health effects of microplastics (NTP, 2019):

1. **Presumed** to be a hazard to humans.
2. **Suspected** to be a hazard to humans.
3. **Not classifiable** as a hazard to humans.

Figure 6. Quality and Strength of the Evidence

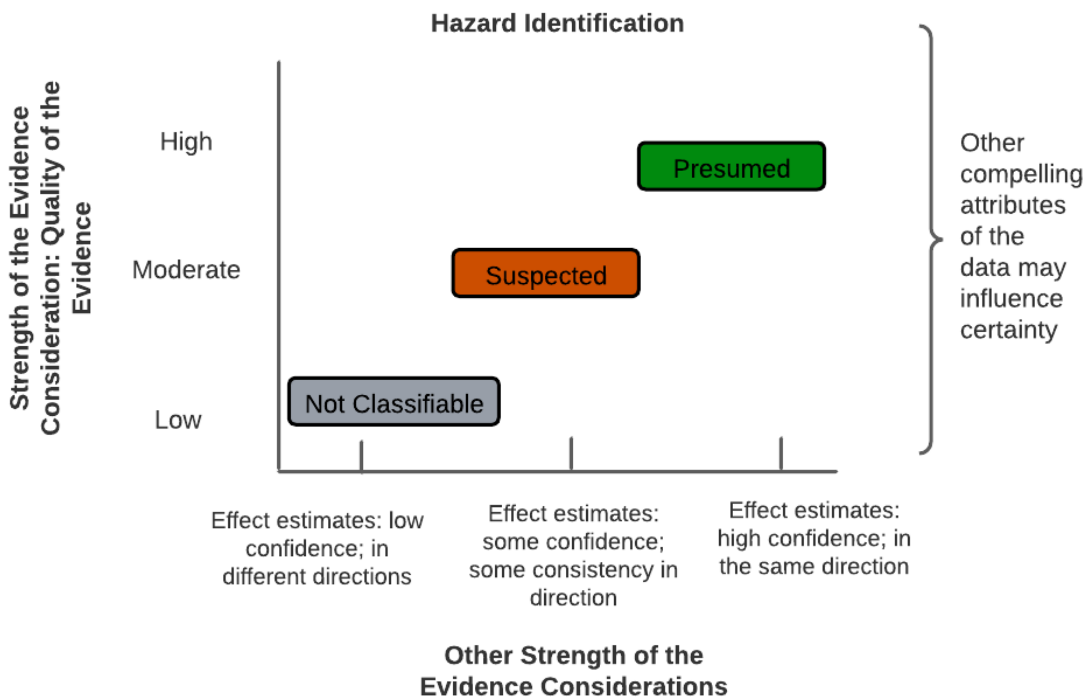


Source: CalSPEC, 2023

This hazard identification scheme is depicted graphically in Figure 7. Detailed information on the rapid review process and results can be found in:

Appendix A: Microplastics Rapid Review Protocol
Appendix B.1: Full Text Exclusions Rationale
Appendix B.2: Study Characteristics
Appendix B.3: Table of Results
Appendix C.1: Risk of Bias Ratings and Justification
Appendix C.2: Quality of the Evidence Ratings

Figure 7. Hazard Identification Scheme (Based on Nonhuman Animal Evidence When No Human Evidence Is Available)



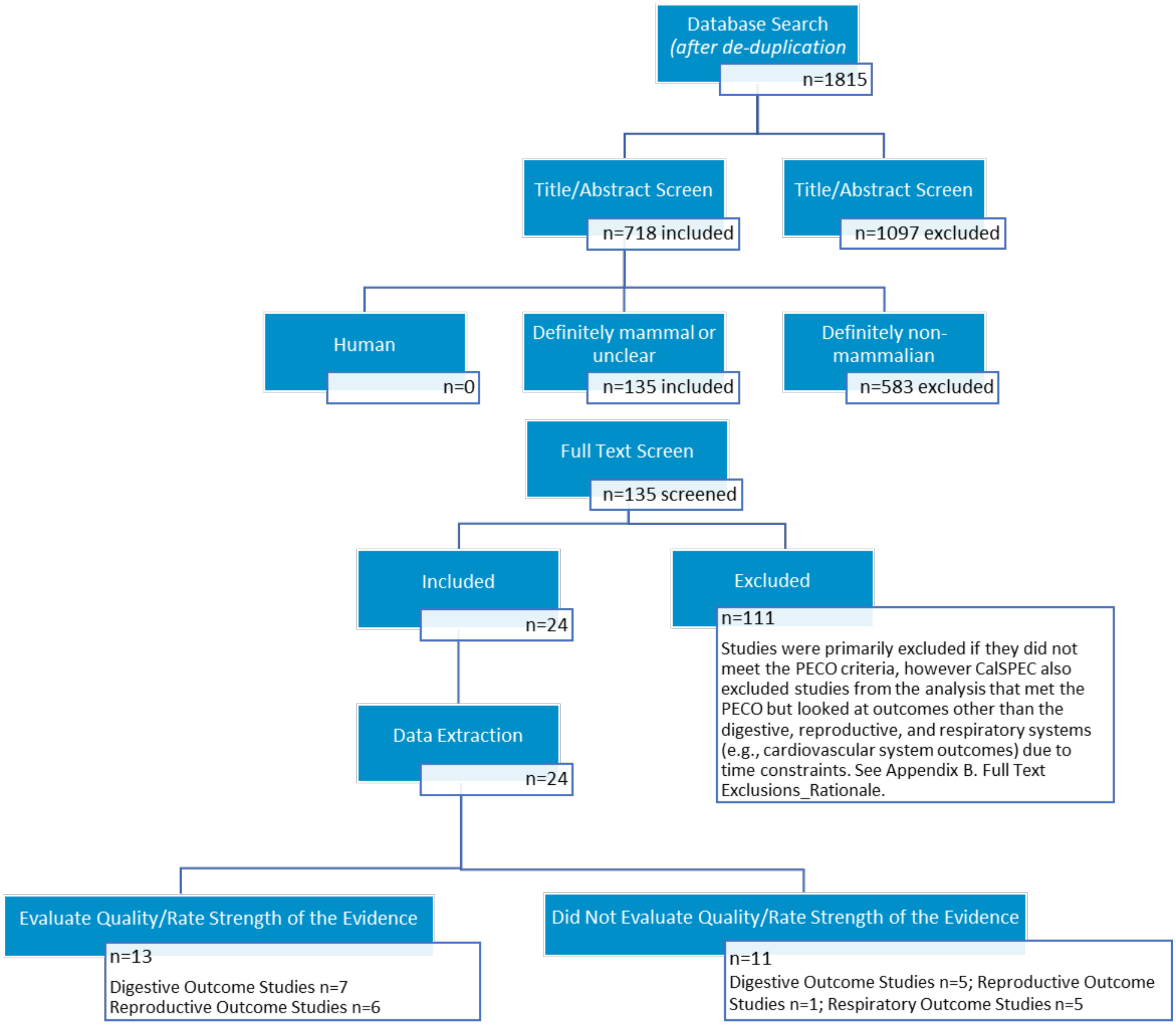
Source: CalSPEC, 2023, based on NTP, 2019.

Findings

Of 1,815 studies screened for inclusion, CalSPEC identified 24 studies (12 digestive, 7 reproductive, and 5 respiratory) that met initial eligibility criteria (Figure 8) and were fully abstracted. These studies overwhelmingly exposed rodents (rats or mice) to polyethylene and polystyrene microplastics in water. The remaining 1,791 studies were excluded for not meeting CalSPEC's inclusion criteria or for addressing outcomes beyond the scope of this report, including studies that evaluated immune outcomes, neurological outcomes, cardiovascular outcomes, musculoskeletal outcomes, urinary outcomes, and dermal outcomes. Among the 24 abstracted studies, 13 (7 digestive, 6 reproductive) chronically exposed rats or mice to multiple concentrations of microplastics. These studies were fully evaluated for quality and strength of evidence. The remaining six studies (5 digestive, 1 reproductive) were set aside because they chronically exposed rodents to a single concentration of microplastics. The five respiratory studies were set aside due to time constraints.

Studies covering digestive and respiratory outcomes were conducted in China, France, and the Republic of Korea; reproductive outcome studies were conducted exclusively in China. Some publications were produced by the same lab group, raising the possibility that errors in method or approach might be propagated across multiple studies. Two lab groups produced two digestive papers each (Choi et al., 2021b; Choi et al., 2021a; Jin et al., 2019; Lu et al., 2018), while another published three reproductive papers (An et al., 2021; J Hou et al., 2021; Li et al., 2021).

Figure 8. CONSORT Diagram of Rapid Systematic Review Study Eligibility



Source: CalSPEC, 2023.

Rodent-to-Human Exposure Comparison

To determine whether the doses administered to animals in reviewed studies were comparable to plausible levels of human environmental exposure, CalSPEC estimated expected human concentrations based on reported rodent dosing and concluded that exposure concentrations for the rodents in these studies was generally within the range of daily microplastics intake for humans for the larger microplastics. However, intake for humans for smaller microplastics (<1 µm) is generally unknown. In addition, given the many factors that can influence susceptibility to exposure in humans — including intrinsic factors such as genetics and life-stage and extrinsic factors such as other chemical exposures and social stressors such as poverty — it is assumed that risks observed at higher exposures can also be observed at lower levels of exposure and that a ‘no-risk’ level cannot be assumed (NRC, 2009).

Digestive System Effects

CalSPEC evaluated six outcomes across seven studies (Table 11) relating to the small or large intestines of the digestive tract, focusing on apical endpoints (in this case, gross or microanatomic colonic and small intestinal effects) and biological outcomes grouped into the following key characteristics of carcinogens:

- Oxidative stress;
- Chronic inflammation;
- Immunosuppression;
- Receptor mediated effects (hormones); and
- Cell proliferation (e.g., Goblet cell count).

Based on a detailed review of each study (see below), CalSPEC rated the overall quality of evidence linking microplastics to harmful health effects on the digestive system as “moderate.”

Table 11. Digestive Outcomes for which CalSPEC Evaluated Quality and Strength of Evidence

Reference	Study Population	Microplastic Size & Type	Exposure Route/ Frequency/ Duration/ Concentration	Outcomes*
Jin et al., 2019	24 mice	5 µm Polystyrene	Water ingestion/ Continuous/6 weeks/ 100 µg/L, 1,000 µg/L	• Apical: gross or micro-anatomic colon effects
Lu et al., 2018	40 mice	0.5 µm, 50 µm Polystyrene	Water ingestion/ Continuous/5 weeks/ 100 µg/L, 1,000 µg/L	• Apical: gross or micro-anatomic colon effects
B. Li et al., 2020	80 mice	10–150 µm Polystyrene	Food ingestion/ Daily/5 weeks/ 2 µg, 20 µg, 200 µg	• Key characteristic: Chronic inflammation
Choi et al., 2021a	40 mice	500 nm Polystyrene	Water ingestion/ Daily/2 weeks/ 10 µg/g, 50 µg/g, 100 µg/g	• Key characteristics: Chronic inflammation; Oxidative stress
Choi et al., 2021b	24 mice	5 µm Polystyrene	Water ingestion/ Daily/2 weeks/ 10 µg/L, 50 µg/L, 100 µg/L	• Apical: gross or micro-anatomic colon effects • Key characteristics: Alterations in cell proliferation, cell death, or nutrient supply; Receptor-mediated effects

Reference	Study Population	Microplastic Size & Type	Exposure Route/ Frequency/ Duration/ Concentration	Outcomes*
Djouina et al., 2022	39 mice	36 µm, 116 µm (median sizes) Polyethylene	Food ingestion/ Continuous/6 weeks/ 100 µg, 200 µg	• Apical: gross or micro-anatomic colon and small intestine effects • Key characteristics: Chronic inflammation; Immunosuppression
Wen et al., 2022	49 mice	5 µm Polystyrene	Water ingestion/ Daily/90 days/ 100 µg/L, 1,000 µg/L	• Apical: gross or micro-anatomic colon effects • Key characteristics: Changes in cell proliferation, cell death, or nutrient supply; Chronic inflammation; Oxidative stress

Source: CalSPEC, 2023.

* The outcomes column does not contain all the outcomes in the study, only the outcomes prioritized for data extraction.

Primary digestive outcomes assessed

Below is a summary of the experimental studies considered for six outcomes; remaining outcomes are summarized and discussed further in Appendix B.3. All results are from comparisons between groups exposed versus not exposed to microplastics. To determine the quality of the evidence on the health effects of microplastics on mammalian digestive and reproductive systems, CalSPEC evaluated the consistency of the effect estimates across the animal studies, the precision of those effect estimates, and the dose response. This information was then used along with the direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure) and confidence in the association (factors including number and size of studies) to reach a conclusion about the potential human health hazard ("Hazard Conclusion"). See appendices for supporting detail.

Outcome 1: Apical digestive measurements (colon and small intestine)
Overall study quality: Moderate

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact the colon and small intestine in humans based on: a) "moderate" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Five studies evaluated apical measurements on the digestive tract including colon length, villus length, and other histopathological measurements of the colon and small intestine (Choi et al., 2021b; Djouina et al., 2022; Jin et al., 2019; Lu et al., 2018; Wen et al., 2022). Similar measurements were conducted between studies, but not all measurements were the same. One study (Wen et al., 2022) observed significant alterations to the colon including muscular layer width. The same study also found significant colon shortening in the exposed group. Another study (Djouina et al., 2022) observed significant differences in crypt depth but not the villus length in the proximal and distal small intestines for the highest exposed group. The same study also observed a significant increase of the mucosal surface area in the colon epithelium but found opposite or no significant change in staining with neutral and acid mucins in different parts of the digestive system. The third study (Choi et al., 2021b) found a significant decrease in multiple histopathological endpoints; the fourth study (Lu et al., 2018) found a significant decrease of mucus secretion in colon for the exposed group. The final study found a significant decrease of the AB/PAS positive area (area with mucins) in all microplastic exposure groups compared to control (unexposed), but did not exhibit a dose response effect across the groups (Jin et al., 2019).

Outcome 2: Alterations of cell proliferation, cell death, or nutrient supply
Overall study quality: Moderate

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact cell proliferation and cell death in humans based on:a) "moderate" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Two studies assessed cell proliferation and death. The first study showed a significant decrease in number in crypts of Lieberkuhn (intestinal mucosal glands) and goblet cells (cells that secrete mucin) in the exposed group (Choi et al., 2021b). The second study also found a significant decrease in goblet cells (Wen et al., 2022).

Outcome 3: Induction of chronic inflammation
Overall study quality: Moderate

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact chronic inflammation in humans based on:a) "moderate" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Four studies evaluated biomarkers (e.g., inflammatory cytokines) related to chronic inflammation. Cytokines such as tumor necrosis factor-α (TNF-α), IL-6, IL-10, and IL-1α were measured in multiple studies. TNF-α levels significantly increased in the colon (Wen et al., 2022) and the intestine (Choi et al., 2021a), but for one study, TNF-α levels were not significantly different regardless of the exposed group in colon and small intestine (Djouina et al., 2022). IL-6 also significantly increased in the colon (Wen et al., 2022) and all (Djouina et al., 2022) or part (Choi et al., 2021a) of the small intestine. IL-10 (anti-inflammatory cytokine) significantly decreased in the colon (Wen et al., 2022) but not in intestinal serum (B. Li et al., 2020). Finally, IL-1α levels significantly increased in the intestine in two studies (Choi et al., 2021a; B. Li et al., 2020). For one study, there are two proteins related to inflammation (iNOS and COX-2) that were significantly increased in the exposure group compared to the control (Choi et al., 2021a). Eight other cytokines were measured in specific studies and most of them had significant changes (increase or decrease, depending on the specific cytokine) between control and exposed groups.

Outcome 4: Induction of oxidative stress
Overall study quality: Low

Hazard Conclusion*: Impacts of microplastics exposure on oxidative stress are not classifiable based on: a) "low" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Two studies examined markers indicating increased oxidative stress in the colon, serum, and intestine. There is no overlap between specific outcome measurements. The first study (Wen et al., 2022) found significant changes for glutathione, superoxide radical, and malondialdehyde concentrations in the colon. The second study (Choi et al., 2021a) found a significant increase in levels of reactive oxygen species concentration, superoxide radical activity and expression, and Nrf expression in the intestine. Both studies found significant effects for all chemicals and biomarkers tested between the control and exposed group.

Outcome 5: Immunosuppressive effects
Overall study quality: Moderate

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact immunosuppression in humans based on: a) "moderate" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Only one study (Djouina et al., 2022) measured biomarkers that relate to the immune system, reporting significant reduction in immunophenotype populations (CD4 T lymphocytes, CD8 T lymphocytes, dendritic cells, and inflammatory monocytes), neutrophils (granulocytes in white blood cells), and anti-inflammatory macrophages (plays a critical role in inflammation). Change in cell populations may not directly relate to immunosuppression, but they do relate to the immune system and could produce an immunomodulation effect.

Outcome 6: Modulation of receptor-mediated effects (hormones)
Overall study quality: Low

Hazard Conclusion: *Impacts of microplastics exposure on hormones are not classifiable based on: a) "low" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

One study (Choi et al., 2021b) measured hormonal changes in the mid colon. Mid-colonic concentrations of cholecystokinin (CCK), which is a peptide hormone responsible for digestion of fat and protein, and gastrin, a hormone that stimulate gastric juice secretion, were significantly reduced.

Other digestive outcomes considered but evidence not fully rated

CalSPEC also narratively assessed the following other key characteristics: alterations in DNA repair or genomic stability and induction of epigenetic alterations. A summary of these narrative assessments is provided in Appendix B.3. Overall, these studies were supportive of conclusions outlined above and added confidence in the overall rating of suspected hazard.

Digestive System Conclusion

Across outcomes that were fully evaluated, CalSPEC found that exposure to microplastics is suspected to be a digestive hazard to humans, including cancer.

Reproductive System Effects

CalSPEC evaluated six reproductive system studies (Table 12). Two studies (An et al., 2021; J Hou et al., 2021) evaluated female endpoints (including hormone level changes and impacts to follicles) and four (B Hou et al., 2021; Huang et al., 2022; Jin et al., 2022; Li et al., 2021) evaluated male endpoints (including sperm damage, testicular damage, and hormone level changes). Studies that assessed hormone levels were also included, as hormonal changes are a key characteristic of reproductive toxicants that may also impact reproductive health directly (Arzuaga et al., 2019; Luderer et al., 2019; Smith Martyn et al., 2016).

Table 12. Reproductive Outcomes for which CalSPEC Evaluated Quality and Strength of Evidence

Reference	Study Population	Microplastic Size & Type	Exposure Route/Frequency/ Duration/ Concentration	Outcomes*
An et al., 2021	32 female rats	0.5 µm Polystyrene	Water ingestion/ Continuous/90 days/ 0.015 mg, 0.15 mg, 1.5 mg	• Apical: Female reproductive outcomes (follicles/ovarian reserve capacity) • Key characteristic; Hormone receptor signaling; reproductive hormone production, secretion, or metabolism
B Hou et al., 2021	40 male mice	5 µm Polystyrene	Water ingestion/ Daily/35 days/ 100 µg/L, 1,000 µg/L, 10 mg/L	• Apical: Male reproductive outcomes (sperm/sperm-related outcomes)
J Hou et al., 2021	32 female rats	0.5 µm Polystyrene	Water ingestion/ Daily/90 days/ 0.015 µg/g, 0.15 µg/g, 1.5 µg/g	• Apical: Female reproductive outcomes • Key characteristic: Alterations in hormone receptor signaling and/or reproductive hormone production, secretion, or metabolism
Li et al., 2021	32 male rats	0.5 µm Polystyrene	Water ingestion/ Daily/90 days/ 0.015 mg, 0.15 mg, 1.5 mg	• Apical: Male reproductive outcomes (Sperm/Sperm related outcomes)
Huang et al., 2022	32 female mice	100 nm Polystyrene	Water ingestion/ Continuous/21 days/ 0.1, 1 and 10 mg/L	• Apical: Male reproductive outcomes (sperm/sperm-related outcomes)
Jin et al., 2022	105 male mice	0.5 µm, 4 µm, 10 µm Polystyrene	Water ingestion/ Continuous/180 days/ 100 µg/L, 1,000 µg/L	• Apical: Male reproductive outcomes (sperm/sperm-related outcomes) • Apical: Male reproductive outcomes (testicular damage) • Key characteristic: Alterations in production and levels of reproductive hormones or hormone receptor levels/functions

Source: CalSPEC, 2023.

*The outcomes column does not contain all the outcomes in the study, only the outcomes prioritized for data extraction. For greater detail on outcomes, including specific p values, please refer to Appendix B.3.

Primary reproductive outcomes assessed

Below is a summary of the studies considered for these outcomes. The remaining outcomes not evaluated in this review are discussed further in Appendices B.2 and B.3.

Outcome 7: Apical outcomes: Sperm quality and testicular damage effects
Overall study quality: High

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact sperm quality and testicular health in humans based on: a) "high" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Four studies evaluated effects of microplastics exposure on varying levels of sperm function (B Hou et al., 2021; Huang et al., 2022; Jin et al., 2022; Li et al., 2021). Studies found trends in declines in living sperm, sperm concentrations, and sperm motility as well as increase trends in sperm malformation (also termed as deformity or abnormality). Only one study (Jin et al., 2022) was blinded during the sperm malformation and viability measurement. All studies reported positive associations between increasing microplastics and decrease in measures of sperm quality/quantity. One study also found significant decrease and dose-response effects between control and exposed groups on testicular morphometric parameters, seminiferous tubular diameter, and germinal cell thickness (Jin et al., 2022).

Outcome 8: Apical outcome: Female follicular effects
Overall study quality: Moderate

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact female follicles in humans based on: a) "moderate" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

Two studies evaluated the effects of microplastics on female follicles (An et al., 2021; J Hou et al., 2021). Both studies found a significant decrease in the number of growing follicles for the highest exposed group and a consistent dose-response relationship. For both studies, five random visual fields were used to assess the number of growing follicles via microscope imaging for each rat model (six from each group). It is unclear whether five images were sufficient to qualitatively assess the measurement, but the authors do refer to previous literature for their methodology.

Outcome 9: (Male) Alters production and levels of reproductive hormones OR alters hormone receptor levels/functions; (Female) alters hormone receptor signaling; alters reproductive hormone production, secretion, or metabolism
Overall study quality: Moderate

Hazard Conclusion: *Exposure to microplastics is suspected to adversely impact reproductive hormones in humans based on: a) "moderate" quality of the body of evidence; b) direction of the association (i.e., consistent evidence of adverse health effects occurring due to microplastic exposure); and c) confidence in the association considering factors including number and size of studies.*

There were three studies that measured hormone level changes. Two studies found significant changes in Anti-Müllerian hormone (AMH) concentration: one in serum (J Hou et al., 2021) and the other in ovaries (An et al., 2021). The third study (Jin et al., 2022) found significant decrease in luteinizing hormone (LH), follicle-stimulating hormone (FSH), and testosterone concentrations in serum.

Other reproductive outcomes considered, but evidence not fully rated

Several other studies assessing key characteristics of reproductive toxicants were considered but not fully evaluated for quality and strength of evidence. These studies were generally supportive of the hypothesis that microplastics cause reproductive system harm but were not considered in reaching CalSPEC's overall conclusion.

Reproductive System Conclusion

Across outcomes that were fully evaluated, CalSPEC concludes that exposure to microplastics is suspected to be a hazard to the human reproductive system.

Respiratory Tract Effects

This narrative summary of data from the five respiratory studies that met CalSPEC's eligibility criteria were not evaluated for study quality or strength of evidence (Table 13). CalSPEC provides these studies as informative for further research, including a rigorous review of this data. In most of these studies, mice or rats were exposed to microplastics via inhalation. The outcomes from these studies included decreased pulmonary function, body weight changes, organ coefficient (calculated as organ weight divided by body weight) changes, changes to inflammatory cytokines, and increased pulmonary mucus production. The summary of outcomes is categorized in Table 13 according to the descriptions provided in the original publications.

The incomplete evaluation process of the respiratory literature prevents CalSPEC from drawing conclusions about microplastic hazards to the human respiratory system; however, CalSPEC suspects that, based on the literature reviewed, respiratory harms from microplastics exposure are likely. Further work is needed to confirm this preliminary finding.

Table 13. Summary of Data Extracted from Respiratory Outcome Studies (No Quality or Strength of Evidence Evaluation)

Reference	Study Population	Microplastic Size & Type	Exposure Route/Frequency/ Duration/Concentration	Narrative Summary of Outcomes*
Lim et al., 2021	40 rats	0.10 µm Polystyrene	Air inhalation/ Daily/ 6hrs per day, 5 days a week for 2 weeks/ 0.75×10^5 particle/cm^3 ± 20%; 1.50×10^5 particle/cm^3 ± 20%; 3.00×10^5 particle/cm^3 ± 20%	• Fibrosis in lung tissues • Changes to organ weights Hematological changes • Serum biochemistry changes • Other changes in lung
Lu et al., 2021	Unclear on total study population, mice	1–5 µm Unclear	Saline inhalation/ Every 3 days/ 24 days/ 300 µg/µL	• Other changes in lung • Aggregation of macrophages • Phagocytosis of MP particles by macrophages • Increased pulmonary mucus production • Increase in Th1 type TNF-α • Alterations in gene expression • Changes to immunoglobulin levels • Changes to inflammatory cytokine levels

Reference	Study Population	Microplastic Size & Type	Exposure Route/Frequency/ Duration/Concentration	Narrative Summary of Outcomes*
Y. Li et al., 2022	40 mice	< 1 µm Tire wear microplastic particles	Saline inhalation/ Daily/ 28 days/ 0.125 µg/g, 0.5 µg/g, 1 µg/g	• Decreased pulmonary function • Pulmonary histopathological changes • Decreased E-cadherin • Body weight changes • Organ coefficient changes • Inflammatory cell changes • Collagen deposition • MiRNA expression profile changes
Fan et al., 2022	20 rats	100 nm, 500 nm, 1 µm, 2.5 µm Polystyrene	Saline inhalation/ Unclear/ 14 days/ 0.5 mg/200 µL, 1 mg/200 µL, 2 mg/200 µL	• Lung injury • Body weight changes • Changes to inflammatory cytokines • LncRNA changes • CircRNA changes • Identification of differentially expressed circRNAs and lncRNAs
X. Li et al., 2022	36 mice	5 µm Polystyrene	Water inhalation/ 3 times a week/ 3 weeks/ 1.25 µg/g, 6.25 µg/g	• Pulmonary fibrosis • Alveolar epithelial injury Activation of Wnt/β-catenin signal pathway • Induction of oxidative stress

Source: CalSPEC, 2023.

* This column does not contain all the outcomes in the study, only the outcomes prioritized for data extraction.

Strengths and Limitations of the Rapid Review

This rapid review has several noteworthy strengths and limitations.

Strengths

- CalSPEC prioritized outcomes where data relevant to human health was most available and would be of higher confidence.
- CalSPEC used scientifically rigorous methods recommended by the National Academy of Sciences, Engineering, and Medicine to evaluate the health effects of environmental contaminants.
- This work allows CalSPEC to apply the concepts of key characteristics to illuminate the importance of using mechanisms/biological pathways to understand health risks. These efforts are in alignment with the State of California's current efforts to advance approaches that use biological and mechanistic data to identify potential human health harms.

- CalSPEC reports the significant health effect findings induced by microplastics based on statistical relevance.

Limitations

The limitations of this rapid review relate both to the current state of the science and to the specific methods CalSPEC employed in producing the review.

Limitations related to the state of the science include:

- **Lack of human studies.** CalSPEC found no studies examining the effects of microplastics exposure on human health. This may be due to lack of appropriate resource allocation to address the challenges of conducting studies in human populations including measuring exposures and allowing sufficient time for adverse outcomes to manifest (Akhbarizadeh et al., 2021).
- **Possible publication bias**. Health effects of microplastics is a nascent field, and CalSPEC conclusions are based on available evidence. It is possible that studies showing null effects microplastics were never submitted or accepted for publication.
- **Unmeasured endpoints.** This review was limited to apical and mechanistic endpoints that were reported in published studies. Other important endpoints may not have been measured or reported. Further, CalSPEC reports that there are studies evaluating multiple other endpoints that could be informative to a more expansive review.
- **Limited range of exposures.** Included studies used manufactured microplastics and did not address effects of microplastics degraded from primary sources such as fabrics and tires. Nor did the studies address aggregate exposures through multiple exposure routes (e.g., water and food exposures together) or the effects of chemicals released from degraded plastics.
- **Inattention to human variability and susceptibility.** The literature provided little data on exposures during sensitive life stages (e.g., child development) nor did it clarify how microplastic exposure could exacerbate existing environmental stressors in a community (e.g., poverty, racism, cumulative exposures) in humans, both of which are known to result in increased risk of health effects from environmental exposures.

Limitations related to the rapid review approach:

- **Not all outcomes reported in the included studies were evaluated for quality and strength of evidence.** Had these outcomes been evaluated, it is possible that some would show adverse health effects and others not. Nevertheless, the overall conclusions of this report would be very unlikely to change.
- **Only rodent studies included.** Studies on other species such as zebrafish have been published; their inclusion in the future, along with more expansive reviews, would augment the robustness of this report's findings.
- **Tradeoffs between speed and rigor.** The rapid review process omits certain methodological steps normally incorporated into a traditional systematic review. A full systematic review would further enhance confidence in CalSPEC's conclusions.
- **Focus on subset of data.** The rapid review focuses on studies that have multiple exposures for the digestive and reproductive system; other studies of one exposure could add to the

evidence base. Further, CalSPEC did not do quantitative dose-response analysis nor meta-analysis and focused on p values. Additionally, quantitative analysis could strengthen CalSPEC's conclusions as it considers more of the data comprehensively.

- **Timing of search.** As the search for relevant evidence was conducted in July 2022, it is possible that more recent publications may have been eligible for inclusion in the review and offer additional insights into the health hazards of microplastics exposure.

Conclusions about the Human Health Effects of Microplastics

Based on the available evidence from experimental studies in rodents, CalSPEC concludes that microplastics are suspected to promote deleterious human health effects in the reproductive and digestive systems. Although respiratory tract studies were not evaluated as rigorously, CalSPEC concludes that respiratory harms from microplastics are also likely suspected. CalSPEC recognizes that these conclusions are likely an underestimation of the true harm of microplastic exposure given the limitations outlined above.

CHAPTER 4: MICROPLASTICS POLICIES

What is known about this topic? The Nicholas Institute Plastics Policy Inventory is a searchable database containing hundreds of plastic-related public policies. However, no recent comprehensive review of microplastics policies has been performed.

What this report adds: This review used the Plastics Policy Inventory, legislative databases, and other online sources to identify approximately 51 laws addressing microplastics at multinational, national, and state or provincial levels of government. Most existing legislation is concentrated in Europe and California. Current policies address microplastics research, microbeads, microfibers, and vehicle tires. Large research gaps remain, and — aside from restrictions on microbeads — the legislative landscape is thin. Furthermore, the effectiveness of existing policies is unknown, largely because rigorous impact evaluations have not yet been performed.

What are the implications for policy? Coordinated national or international efforts are needed to develop standardized definitions and methods for measurement and analysis of microplastics. International, national, and state-level policy initiatives addressing microfibers and tires are generally less robust than those addressing microbeads; these areas are fertile ground for policy development. Finally, little is known about the impact of policies designed to mitigate microplastics pollution, either directly (e.g., through bans on microbeads in cosmetics) or indirectly (e.g., through policies to discourage plastic bag use). Rigorous study of the environmental and economic impact of microplastics mitigation policies is needed to assure that mitigation achieves maximal benefit at the lowest cost and with the fewest unintended consequences.

Introduction

Microplastics are both increasingly prevalent in the environment and increasingly suspected as a threat to health (Chapters 2 and 3). In recognition of these facts, governments at various levels have supported research to understand the impact of microplastics and have implemented policies to mitigate resulting harm. California has been a leader in these efforts, but it has not been alone. The purpose of this chapter is to describe the current landscape of government actions concerning microplastics and to assess, where possible, their impact on microplastics production, use, distribution, and mitigation. This information is intended to inform evidence-based public policy deliberations in California and beyond.

This chapter is divided into five main sections: 1) summary of California microplastic policy actions to date; 2) description of government actions that mandate research on the environmental and human health impacts of microplastics; 3) description of government actions to limit or mitigate the harms of microplastics, organized according to source (microbeads, textiles, and tires); 4) high-level overview of multinational agreements and treaties on microplastics; and 5) description of selected *macro*plastic policy evaluations that may be instructive for formulating future *micro*plastic policy evaluations. Each subsection begins with a summary table of relevant policy actions organized chronologically within level of government, and which provides a narrative description of the history and structure of the representative policy actions within each category.

The CalSPEC Microplastics (MP) Policy Catalog (Appendix D) is a searchable inventory of the government actions discussed in this chapter.

This chapter does not cover laws addressing first-generation or "virgin" plastics (e.g., plastic bags, single-use containers), which are the source of most microplastics. Efforts to control the release of these *macro*plastics into the environment, principally through recycling mandates, are beyond the scope of this report. Additional information on *macro*plastics can be found in *Chapter 2: Microplastics Explained*.

Methods

The review yielded 51 government actions that met the search criteria. The project scope was limited to laws, actions, and initiatives enacted between 2010 and 2022. Information obtained by CalSPEC researchers was gathered between June and September 2022.

CalSPEC used three main sources to develop a comprehensive list of government actions on microplastics: the Nicholas Institute Plastics Policy Inventory; legislative databases; and government and nonprofit websites. Government actions of interest included those that define microplastics, directly reference microplastics, support research on microplastics, or adopt policy interventions to reduce environmental or human exposure to microplastics. These actions were carried out by developed and developing nations, multinational rulemaking bodies (e.g., United Nations Environment Assembly, G7 countries) and state governments.

Although macroplastics are the primary contributor to microplastics in the environment (see *Chapter 2: Microplastics Explained*), this policy review excludes laws or actions that address macroplastics exclusively (e.g., laws limiting the use of single-use containers or plastic bags). Despite their obvious relevance to microplastics mitigation, policies to reduce production of or subsidies for oil and gas feedstocks for plastics are also beyond the scope of this review.

Policy Data Sources

Nicholas Institute for Energy, Environment & Sustainability, Duke University, Plastics Policy Inventory

The Nicholas Institute's Plastics Policy Inventory (Plastics Policy Inventory) is a searchable database that includes policy documents focused on plastics pollution. As of CalSPEC's microplastics report search date, the inventory was last updated February 2022. The Plastics Policy Inventory contains laws, government actions, and multinational agreements — some of which target microplastics — and is the primary source of most of the government actions listed in the CalSPEC Microplastics Policy Catalog. Search terms were limited to "microplastics," "microbeads," "textiles," "tires," and "microplastics research." CalSPEC selectively included references that describe legislation and national requirements for microplastics research.

CalSPEC also obtained information specific to microplastics from a complementary publication from the Nicholas Institute for Energy, Environment & Sustainability, entitled *20 Years of Government Responses to Global Plastic Pollution,* which provides narrative summaries of global plastic policy actions referenced in the Plastics Policy Inventory (Karasik et al., 2020). The report spans from 2000 to 2019. CalSPEC used references from this report to inform the narrative.

Legislative databases

CalSPEC searched two legislative databases — LegiScan and BillTrack50 — to supplement findings from the Plastics Policy Inventory. CalSPEC used these databases because they include accurate information across all 50 states and can easily be accessed by stakeholders for future use. The search was limited to enacted laws that included the term "microplastics," thereby ensuring broad capture of all microplastics laws within the two databases.

Government and nonprofit websites

The Plastics Policy Inventory did not identify policies addressing microplastics from tires and textiles. CalSPEC therefore reviewed the Organization for Economic Co-operation and Development (OECD) report, entitled *Policies to Reduce Microplastics in Water: Focus on Textiles and Tires* (OECD, 2021). This report lists several government actions to reduce water-borne microplastics derived from textiles and tires.

Lastly, CalSPEC sought to update incomplete (e.g., evolving legal definitions of microplastics) and outdated information (e.g., new publication released, working group formed) found in the Plastics Policy Inventory. Supplemental information was discovered through searches of government and nongovernmental organizational websites and other publicly available sources. Pertinent governmental websites were identified through a Google search that combined the country name with "environment" and "agency or department." Within each agency website, broad search terms included "microplastics," "microbeads," "textiles," and "tires" or "tyres."

Spotlight on Microplastics Legislation in California

California State Entities with Microplastics Oversight Responsibilities
California Department of Public Health
California Environmental Protection Agency
State Water Resources Control Board
Department of Resources Recycling and Recovery (CalRecycle)
State Air Resources Control Board
Department of Toxic Substances Control: Safer Consumer Products Program
California Natural Resources Agency
California Ocean Protection Council
California Coastal Commission
California Department of Fish and Wildlife
California Fish and Game Commission
Office of Environmental Health Hazard Assessment
State Lands Commission

California has enacted four major pieces of legislation addressing microplastics.

- **AB 258** (CA Legislature, 2007) restricts discharges of preproduction plastics (microplastic pellets and colorants used for plastics production) to waterways that occur during the manufacturing, handling, and transporting process.
- **AB 888** (CA Legislature, 2015) prohibits the sale of personal care products with plastic microbeads.
- **SB 1422** (CA Legislature, 2018) requires the State Water Resources Control Board to develop standardized definitions and metrics for microplastics in drinking water and to conduct annual testing for microplastics in drinking water. Pursuant to this legislation, the State Water Resources Control Board recently developed standardized analytical methods for monitoring microplastics (De Frond et al., 2022).
- **SB 1263** (CA Legislature, 2018) directed the California Ocean Protection Council to develop a Statewide Microplastics Strategy (described below) to reduce microplastics pollution of the marine environment (OPC, 2022). The strategy, released in February 2022, calls for broad actions to address microplastics through:
    - Elimination of plastic waste at the source;
    - Pathway interventions, such as stormwater or wastewater filtration, that reduce transport of microplastics from specific sources into California waters; and
    - Education to inform the public and industries of microplastics sources, impacts, and solutions.

The Statewide Microplastics Strategy offers further policy actions to address source-specific primary and secondary microplastics, including:

- Microbeads
    - By 2023, expand statewide bans of microbeads in personal care products to include household and industrial cleaning products.
- Microplastic fibers (secondary microplastics released from textiles)
    - Evaluate existing technologies (e.g., filters in washing machines and dryers);
    - Modify synthetic textile composition to reduce synthetic microfiber emissions;
    - Develop fiber-shedding standards for textiles; and
    - Extend producer responsibility strategies.
- Microplastics from tires
    - Evaluate tire abrasion rates under various road surface and environmental conditions;
    - Stimulate product design alternatives;
    - Develop a policy framework to advance roadway and pavement designs (to reduce wear and tear particles); and
    - Develop a framework to reduce vehicle miles traveled.

Separate from bills directly targeting microplastics, SB 54 (CA Legislature, 2022) requires 65% of all packaging in the state to be recyclable or compostable by 2032 and a 25% reduction of all plastic packaging by 2032. Reducing the manufacture and use of macroplastics could have a significant impact on microplastics pollution. California's law is the most ambitious in the nation and joins others that recently passed legislation on hard-to-recycle plastics (New Zealand, European Union, etc.).

Microplastics Policies

CalSPEC identified two major groups of microplastics policies enacted outside California: those seeking to promote research on microplastics occurrence and effects, and those seeking to limit microplastics pollution. In addition, CalSPEC found several international agreements aimed at reducing microplastics in the environment. The following sections address each of these broad groupings in turn.

Government Support for Microplastic Research

Governments have increasingly recognized that lack of methodologic standards and other research gaps are barriers to informed decision-making about prevention, mitigation, and resource allocation decisions. Table 14 summarizes 11 laws that mandate or allocate funding for microplastics research. CalSPEC found eight laws and two voluntary government-led actions advocating for additional research on microplastics prevention and mitigation. A majority of laws and actions were promulgated in the US and Europe; few are source-specific.

Table 14. Multinational, National, and State Actions on Microplastics Research

Country	State	Year	Action Title	Description
National and Multinational Level				
Netherlands	N/A	2012	Marine Strategy for the Dutch Part of the North Sea	Mandates research on mitigation measures for a range of use-based microplastics on human health, established a voluntary reduction of microbeads in cosmetic products beginning 2017, created new monitoring to measure microplastics in river basins, a call to action to the EU to ban microplastics in detergents, standardizing of methods when measuring the effects of microplastics to organisms and ecosystems, and conducting research on microplastics in tires.
Sweden	N/A	2017	Regulation on state subsidies to reduce emissions of microplastics to the aquatic environment	Provides financial incentives to be granted by the Swedish Environmental Protection Agency for investments that protect marine and inland waters from microplastics and other pollutants.
Secretariat of the Pacific Regional Environment Program (SPREP)*	N/A	2018	SPREP Pacific Regional Action Plan Marine Litter	Commits to implement a standardized marine litter and microplastics data collection system and app for the Pacific by 2018, and support the development of a global legal framework to address marine litter by 2021.
Norway	N/A	2019	Norwegian Development Program to Combat Marine Litter and Microplastics Program	Commits funding to establishing a new program intended to research microplastics impacts and support Global South countries' efforts to reduce marine litter and microplastics.

Country	State	Year	Action Title	Description
United States	N/A	2020	S.1982: Save Our Seas Act 2.0	Required a number of studies on effects of microplastics on human health and the environment. The law tasked the U.S. Environmental Protection Agency to submit a microplastics report providing a science-based definition of "microplastics," recommendations for standardized monitoring, and an assessment of the extent to which microplastics are present in food supplies and drinking water.
Malaysia	N/A	2021	National Marine Litter Policy and Action Plan 2021-2030	Agreed to cooperate with other member countries in implementing UNEA and Basel Convention agreements, commits to promoting public awareness on impacts of microplastics, define and improve research on both microplastics and nanoplastics.
Subnational Level				
United States	California	2018	SB 1263	Requires the Ocean Protection Council to adopt and implement a Statewide Microplastics Strategy related to microplastic materials that pose an emerging concern for ocean health. The bill requires the OPC to submit the Statewide Microplastics Strategy to the Legislature on or before December 31, 2021, and to report on the implementation of the strategy, including findings, recommended policy changes, and any potential need for additional research, on or before December 31, 2025.
United States	Illinois	2019	SB 1392	Provides that, subject to appropriation, the Prairie Research Institute shall conduct a detailed review of the available scientific literature and federal and State laws, regulations, and rules to identify the threat of microplastics to human health and the environment.
United States	New Jersey	2020	S 864	Establishes the Plastics Advisory Council, housing within the state Department of Environmental Protection to study the environmental and public health impacts of single-use plastics and microplastics and shall submit a report to the legislature two years after the effective date of this bill.
United States	Minnesota	2022	H 3765	Appropriates funds from environment and natural resources trust fund to study plastic use in the agricultural supply chain and to research and communicate strategies to reduce the impacts of this plastic use, including water and land contamination from microplastics, PFAS and related compounds; and map urban and suburban soil toxins of concern, such as heavy metals and microplastics, and to test

Country	State	Year	Action Title	Description
				whether pollinator plantings can redistribute these toxins in the soil of yards, parks, and community gardens and reduce exposure to humans and wildlife.
United States	Vermont	2022	H.446: An act relating to miscellaneous natural resources and development subjects	Among many requirements, the Act requires Agency of Natural Resources to submit to the General Assembly a report regarding the prevalence of microplastics and per- and polyfluoroalkyl substances (PFAS) in food waste and food packaging in Vermont, no later than January 15, 2024.

Source: CalSPEC, 2023.

*SPREP is a regional entity based in Samoa focused on climate change and environmental issues affecting small island developing states made up of 21 Pacific Island member countries. The member countries include American Samoa, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, Niue, Northern Marianas, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu and Wallis & Futuna.

National and multinational microplastics research initiatives

Multiple countries have been working independently and cooperatively to encourage microplastics research.

- **Norway,** in 2014, presented to the United Nations Environmental Assembly (UNEA) the initial proposal to enshrine marine litter and microplastic into UNEA Resolution 1/6. The Norwegian Environmental Agency (NEA) has since then engaged on multiple UNEA Resolutions. In 2018, Norway's Prime Minister committed 160 million Euros to a new program on marine litter and microplastics, set to run from 2019-2024. A portion of this funding is allocated to build capacity in Global South Countries. Norway has also worked to identify knowledge gaps and draft strategies to reduce microplastics pollution in the Arctic. A workshop in late 2019 revealed the need to actively monitor microplastic levels; conduct source tracking; analyze and determine processes and life cycle of microplastic pollution; and to create hazard assessment tools to identify microplastic impacts to the environment and human health.
- The **Netherlands** Marine Strategy mandated research on measures to reduce human health impacts of microplastics; research on microplastics in tires; new monitoring to measure microplastics in river basins; and a call urging EU action to ban microplastics in detergents and to standardize methods for measuring effects of microplastics on organisms and ecosystems.
- **Malaysia's** 2021-2030 National Marine Litter Policy and Action Plan (Action Plan) urged cooperation with the Association of Southeast Asian Nations (ASEAN) to implement relevant international laws. The Action Plan seeks to standardize methods for microplastics detection, better define microplastics and nanoplastics, and develop technologies to avoid or reduce microplastic release into the environment. By 2023, Malaysia intends to facilitate cooperation between ASEAN and UNEA and to implement UNEA resolutions.
- In 2017, **Sweden** passed a law, based on Swedish research, allocating funds to the Swedish Environmental Protection Agency to finance research grants that will deepen the knowledge of microplastics pollution and explore mitigation measures.

- An initiative brought forth by **Secretariat of the Pacific Regional Environment Program (SPREP)**, composed of 21 Pacific Island member countries, calls for key metrics and actions to establish a standardized microplastics data collection system by 2019. The Plan requires a progress report, which has yet to be finalized, likely due to delays associated with the Covid-19 pandemic.
- In the **United States**, S. 1982 required studies on the effects of microplastics on human health and the environment. The 2020 law requires the US EPA to submit a microplastics report providing a science-based definitions of microplastics, recommendations for standardized monitoring, and an assessment of the extent to which microplastics are present in food supplies and drinking water. The law also allows the EPA, when distributing grants to state and local governments, to fund projects that reduce microplastics.

Subnational microplastics research initiatives

Several US states have shown interest in microplastics research and strategies. Aside from California's laws SB 1263 and SB 1422, four other US states have shown interest in research to reduce microplastics impacts.

- In 2019, **Illinois** passed SB 1392 (Illinois G.A., 2019), which required the Prairie Research Institute — a think tank organization housed within the University of Illinois Urbana-Champaign — to conduct a detailed review of the scientific literature and federal and State laws, regulations, and rules to identify the threat of microplastics to human health and the environment. The law also required the Prairie Institute to submit to the Illinois General Assembly (i.e., state legislature) a report of its findings including recommendations for legislative or regulatory actions that the state can take to protect human health and the environment from microplastics. (CalSPEC was unable to find the report on the Prairie Institute or General Assembly website.)
- In 2020, **New Jersey** created under S. 864 a Plastics Advisory Council, tasked with reporting the environmental and public health impacts of single-use plastics and microplastics to the legislature in 2022. (CalSPEC was unable to find any public record of the Plastics Advisory Council meeting(s), or a report submitted to the New Jersey General Assembly.)
- In 2022, **Minnesota** appropriated funds to study plastic use in the agricultural supply chain and to research and communicate strategies to reduce the impacts, including water and land contamination from microplastics as well as per- and polyfluoroalkyl substances (PFAS).
- In 2022, **Vermont** passed H. 446, which requires its Agency of Natural Resources to submit a report to the General Assembly about the prevalence of microplastics and per- and polyfluoroalkyl substances (PFAS) in food waste and food packaging in Vermont. The report, due January 15, 2024, must include recommendations for standard microplastics testing methodology, recommendations to reduce levels of microplastics in the environment, a summary of data gaps in the management of microplastics and recommendations for how to close those gaps, and recommendations for a health-based standard. The law also requires the Secretary of Natural Resources to establish regulations to determine a standard testing methodology and a standard for microplastics and PFAS leakage from food waste facilities, as needed to protect human health and natural resources.

Microbead Prevention and Mitigation Policies

Microbeads are small, round plastic particles used in cosmetics, personal hygiene, and cleaning products. During the 1990s and early 2000s, cosmetic and hygiene companies began using solid plastic microbeads as a cleaner or soft exfoliant in facewash, shower gel, and toothpaste (Dauvergne, 2018). Household and industrial cleaning agents also use microbeads (see *Chapter 2: Microplastics Explained*). As a result, unprecedented amounts of microbeads funneled into wastewater treatment plants and subsequently made their way into rivers, lakes, and oceans (Dauvergne, 2018). In 2014, research led by the Province of Ontario's Ministry of Environment and Climate Change in Canada, found significant quantities of microplastics in water samples from Lake Erie and Lake Ontario, with microbeads comprising 14% of total litter (Ontario Government, 2021).

CalSPEC found 18 laws and two voluntary agreements that ban microbeads (each with various requirements banning manufacture, sale, or distribution) in various types of rinse-off cleaners or soft exfoliants. Table 15. National, Subnational, and Multinational Actions on Microbeads summarizes, in chronological order, the microbead actions taken at various levels of government.

Government actions addressing microbeads began in 2014–15 at the subnational level (Illinois and the Province of Ontario), which motivated national action by Canada and the United States. Other national and subnational jurisdictions followed suit with Argentina being one of the latest national governments to take action.

Table 15. National, Subnational, and Multinational Actions on Microbeads

Country	Subnational	Year	Name of Law or Action	Description
National Level				
United States	N/A	2015	H.R. 1321: "Microbead-Free Waters Act" (Public Law 114-114)	Bans the manufacturing, packaging and distribution of rinse-off cosmetics containing synthetic plastic microbeads, and also applies to products that are both cosmetics and nonprescription (over the counter drugs), such as toothpaste.
Canada	N/A	2016	Microbeads in Toiletries Regulations (SOR/2017-111)	Bans the manufacture or import of any toiletries that contain microbeads, unless the toiletries are also natural health products or nonprescription drugs.
Taiwan	N/A	2016	Restrictions on the Manufacture, Import, and Sale of Personal Care and Cosmetics Products Containing Plastic Microbeads	Bans the manufacture, import, and sale of cosmetics that contain microbeads, such as facial scrub or toothpaste.
England, United Kingdom	England	2017	Environmental Protection Microbeads Regulations	Bans the manufacture of any rinse-off care product that uses microbeads as an ingredient of that product.
New Zealand	N/A	2017	Waste Minimization	Bans "wash-off products" that contain microbeads for purposes of

Country	Subnational	Year	Name of Law or Action	Description
			(Microbeads) Regulations	exfoliation, cleaning, or visual appearance but does not include a medical device or medicine.
Sweden	N/A	2018	Swedish rules on plastic microbeads in cosmetic products	Ban on the sale of cosmetic products containing plastic microbeads that have a cleansing, peeling, or polishing effect.
France	N/A	2018	Decree No. 2017-291 Ban on marketing rinse-off cosmetic products	Bans the sale of rinse-off cosmetic products intended for exfoliation or cleansing containing solid plastic particles, except for natural particles not likely to persist in the environment and spread chemical or biological actives, or to affect animal food chains.
Ireland	N/A	2019	Microbeads (Prohibition) Act 2019	Bans the manufacture of any cosmetic or cleaning product that contains microbeads.
Australia	N/A	2020	Recycling and Waste Reduction Act 2020 and National Plastics Plan 2021	Phases out microbeads in rinse-off cosmetics, personal care, and cleaning products.
China	N/A	2020	Notice No. 80 to forbid the use of microbeads in cosmetics products	Prohibits manufacturing cosmetic products containing plastic microbeads, by the end of calendar year 2020, and ban the sale of products by the end of calendar year 2022.
Argentina	N/A	2020	Law 27602 Plastic Microbeads in Cosmetic Products	Prohibits the production, import, and marketing of cosmetic products and oral hygiene products for dental use that contain intentionally added plastic microbeads.
Subnational Level				
United States	Illinois*	2014	SB 2727 Microbead Ban (Public Act 098-0638)	Bans the manufacture and sale of personal care products containing microbeads.
Canada	Ontario	2015	Bill 75 Microbead Elimination and Monitoring Act	Prohibits the manufacture of microbeads and the addition of microbeads to cosmetics, soaps, or similar products. Also requires frequent water sampling of the Great Lakes.
United States	California*	2015	AB 888: Waste management: plastic microbeads	Prohibits the sale, or offering for promotional purposes, rinse-off personal care products containing plastic microbeads.
Canada	Ontario	2015	Bill 75 Microbead Elimination and Monitoring Act	Prohibits the manufacture of microbeads and the addition of microbeads to cosmetics, soaps, or similar products. Also requires

Country	Subnational	Year	Name of Law or Action	Description
				frequent water sampling of the Great Lakes.
Wales, United Kingdom	Wales	2018	Environmental Protection Microbeads Regulations	Bans the manufacture of any rinse-off personal care product that uses microbeads.
Scotland, United Kingdom	Scotland	2018	Environmental Protection Microbeads Regulations	Bans the manufacture of any rinse-off personal care product that uses microbeads.
Northern Ireland, United Kingdom	Northern Ireland	2019	Microbeads (Prohibition) Act 2019	Bans the manufacture of any cosmetic or cleaning product that contains microbeads.
Multinational Level				
Northeast Atlantic Government**	N/A	2014	OPSAR Commission's Northeast Atlantic Governments' Marine Litter Regional Action Plan	Asks that participating states explore the possibility of reaching a voluntary agreement with industry to phase-out the use of microplastics in personal care products.
G7 Countries	N/A	2018	Ocean Plastics Charter	Urges industry to reduce the use of plastic microbeads in rinse-off cosmetic and personal care consumer products.

Source: CalSPEC, 2023

* California and Illinois are the two states leading the rest of the US in microbead bans. Since 2014, seven states have passed microbead legislation (Colorado, Maine, New Jersey, Wisconsin, Indiana, Maryland, Connecticut) – for brevity they are not included in the table but more information on these laws can be found below.

** Includes Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom.

National microbead bans

With industry support (Dauvergne, 2018), the United States Congress passed H.R. 1321, the "Microbead-Free Waters Act" in 2015, which bans manufacturing, packaging, and distribution of rinse-off cosmetics containing synthetic plastic microbeads. It applies both to cosmetics and nonprescription products (i.e., over the counter drugs, such as toothpaste). Public Law 114-114 (H.R. 1321) defines microbeads as any "solid plastic particle that is less than 5 millimeters in size and is intended to be used to exfoliate or cleanse the human body or any part thereof."

Canada was the second national government to act on microbeads. In 2016, two years after Ontario passed legislation, Canada listed microbeads as a "toxic substance," and announced a nationwide ban on the sale, import, and production of personal care products containing microbeads as exfoliants of cleaners. The ban took effect in 2018.

In 2016, the United Kingdom announced plans to ban microbeads in cosmetics and personal care products by the end of 2017 (UK DERFA, 2016). Subsequently, several other countries passed bans on microbeads between 2016 to 2020; Taiwan, New Zealand, Sweden, France, Ireland, China, and

Argentina passed bans with slightly different requirements. A number of these laws introduced a phase-in approach first banning the manufacture of regulated products, and then in subsequent years banning the sale (see China's law as an example). Almost all of these laws went into effect between the years 2018 and 2022.

Subnational microbead bans

The first states in the US to ban the sale of microbeads were Illinois (2014) and California (2015) with at least seven states following suit in subsequent years. In 2014, Illinois moved to ban the manufacture and sale of microbeads, as legislators responded to rising public concern over research confirming microbead concentrations in the Great Lakes (Eriksen, 2017): SB 2727 Microbead Ban (Illinois G.A., 2014). Shortly thereafter, the Province of Ontario passed a law (Bill 75: Microbead Elimination and Monitoring Act, 2015) that prohibits the manufacture of microbeads and the addition of microbeads to cosmetics, soaps, or similar products (L.A. of Ontario, 2015). The law also requires the Minister of the Environment and Climate Change to ensure that water samples from the Great Lakes are analyzed for the presence of microbeads and that the finding be published on a government website. CalSPEC was not able to find the published results on the ministry's website.

California's version of the microbead ban, AB 888 (CA Legislature, 2015), was passed shortly after Illinois. Beginning January 1, 2020, AB 888 prohibits the sale (or offering for promotional purposes) of rinse-off personal care products containing plastic microbeads. AB 888 exempted products containing less than 1 part per million by weight of plastic microbeads.

In the United States, seven of states followed the lead of Illinois and California (Colorado, Maine, New Jersey, Wisconsin, Indiana, Maryland, Connecticut) to adopt microbead bans. The laws each contain slight variations, such as different restrictions and deadlines. For example, Maryland exempts "biodegradable" microbeads while Connecticut and California ban all microbeads in rinse-off personal care products, including "biodegradable" microbeads (see Appendix D: Microplastics Policy Catalog for details). In the United Kingdom, Scotland, Wales, and Northern Ireland all passed similar laws in 2018–19.

Microbead phase-outs: Voluntary agreements

Two separate actions, one led by a coalition of national governments and the second by Australia, called for a voluntary phase-out of microbeads. First, the 2014 Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Commission developed the Marine Litter Regional Action Plan, which called for voluntary industry agreement to phase out the use of microplastics as a component in personal care and cosmetic products (OSPAR, 2014). If the voluntary agreement proved ineffective, OSPAR would call on the EU to introduce appropriate measures to achieve a 100% phasing out of microplastics in personal care and cosmetic products. Second, Australia recently implemented its 2021 "National Plastics Plan" that encouraged industry to "voluntarily phase out microbeads from 99.3% of rinse-off cosmetic, personal care and cleaning products sold in Australia" (Australian Government, 2021).

Coordinated multinational microbead mitigation policies

Given that microbeads travel across national boundaries, there has been some coordinated multinational action. In 2016 the United Nations Environment Assembly adopted Resolution 2/11 that encouraged "manufacturers to consider impacts of products containing microbeads" and called for more specific actions on microplastics. This attention by a multinational organization parallels actions that the United States, Canada, and other national governments were implementing separately to reduce microbeads in their respective environments. In 2018, the G7 Countries (Canada, France, Germany, Italy, the United Kingdom, and the European Union) agreed to the Oceans Plastics Charter (Charter), which committed signatories to encourage industry to work toward a resource-efficient lifecycle management approach to plastics in the economy and reduce the use of plastic microbeads in rinse-off cosmetic and personal care consumer products by 2020 (G7, 2018). Both of these agreements lack enforcement authority.

Microfiber Prevention and Mitigation Policies

Microfibers (tiny strands of [semi]synthetic fibers originating from textiles, wipes, cigarette filters, fishing gear, etc.) are an emerging environmental concern due to the growing body of research showing pervasive exposure to microfibers and potential impact on the environment and human health (see *Chapter 2: Microplastics Explained*).

CalSPEC found four laws and two voluntary actions aimed at reducing the occurrence of microfibers or studying the impact of microfibers (Table 16). These actions focus almost exclusively on preventing entrance into waterways (via laundry) rather than into land or atmospheric environmental compartments. Most of these efforts originated in the United States. Canada funded research on microfiber release, while California began testing for microfibers in drinking water. France has recently moved to directly address microfibers in laundry machines.

Table 16: Multinational, National, and State Actions on Microfibers

Country	State or Province	Year	Name of Law or Action	Description
National				
Canada	N/A	2018	Zero Plastic Waste Strategy	Provides funding to support research on microfiber release during washing, to design dedicated test methods and to develop sampling methods for microfiber in laundry effluent and wastewaters.
France	N/A	2020	Anti-Waste Law for a Circular Economy	Mandatory requirement for all new professional and household washing machines to be equipped with a microfiber filter by January 1, 2025.
United States	N/A	2020	S. 1982 Save our Seas Act 2.0	Required a number of studies of the effect of microplastics including microfibers on human health and the environment.
Australia	N/A	2021	National Plastics Plan 2021	The Australian government will work with industry to phase-in microfiber filters on all washing machines sold in Australia by 2030.
Subnational				
United States	California	2018	SB 1422 Safe Water Drinking Act: microplastics	Requires the State Water Board, on or before July 1, 2021, to adopt standard methodology to be used in the testing of drinking water for

Country	State or Province	Year	Name of Law or Action	Description
				microplastics (including microfibers), and requires annual testing and reporting of microplastics in drinking water for four years.
United States	Connecticut	2018	House Bill 5360	Requires the state Department of Energy and Environmental Protection to convene a working group of representatives from the apparel industry and the environmental community to develop a consumer awareness and education program about synthetic microfiber pollution.

Source: CalSPEC, 2023.

National microfiber policies

To date, France is the only country to pass legislation requiring a reduction in microfiber shedding from clothing. This was part of a broader anti-waste, "circular economy" law that specifically requires industry to reduce microfibers in the environment. Specifically, the law requires all new professional and household washing machines to be equipped with a microfiber filter by January 1, 2025.

Following suit, Australia's 2021 National Plastics Plan supports an industry-led phase-in of microfiber filters on new residential and commercial washing machines by 2030. Australia had previously, through its microbeads reduction strategy, won industry commitment to phase-in voluntary bans in cosmetic products.

Canada in 2018 issued a Zero Plastic Waste Strategy (ZPWS) that seeks a comprehensive approach to reducing plastics pollution and addresses research gaps on macro and microplastics (Government of Canada, 2022). The ZPWS called for funding to support research on microfiber release during washing and efforts to design dedicated test methods for microfibers in laundry machines and wastewater. In 2021, Canada updated the ZPWS, announcing efforts to better understand the effects of microplastics on wildlife, the environment and human health.

Several laws require the study of microfibers in the environment. In 2020, the US Congress passed "Save Our Seas 2.0 Act," which requires the Interagency Marine Debris Coordinating Committee (IMDCC) to develop a report on microfiber pollution. Specifically, the report must include: 1) a definition of microfiber; 2) an assessment of the sources, prevalence, and causes of microfiber pollution; 3) a recommendation for a standardized methodology to measure and estimate the prevalence of microfiber pollution; 4) recommendations for measures to reduce microfiber pollution; and 5) a plan for how Federal agencies, in partnership with other stakeholders, can act to reduce microfiber pollution during a 5-year period beginning with enactment. The draft report, released fall 2022, calls for prevention and mitigation techniques such as rethinking textile design and production and improving washing machine and dryer filtration systems to reduce microfiber pollution. A final version of IMDCC's report was due in December 2022.

State microfiber policies

California and Connecticut passed laws requiring state agencies to better understand microfiber pollution. California's SB 1422 (CA Legislature, 2018) was the first subnational government to require the State Water Resources Control Board to develop a definition and a standard methodology for quantifying microplastics in drinking water, which also includes monitoring microfiber pollution in drinking water. Additionally, California's Statewide Microplastics Strategy, adopted and implemented by the Ocean Protection Council, includes specific recommendations to address microfiber pollution (OPC, 2018).

Gaps in Microfiber Knowledge

NOAA identified microfiber knowledge gaps:

- Microfiber prevalence in environmental compartments (water, land, air, biota)
- Rates of release of microfiber sources into the environment
- Feasibility of filtration-related mitigation measures in both washing machines and dryers
- Broader impacts of microfiber pollution

The Connecticut state legislature passed HB 5360 (Dubitsky et al., 2018), which requires the state's Department of Energy and Environmental Protection (DEEP) to convene a working group of representatives from the apparel industry and the environmental community to develop a consumer awareness and education program about synthetic microfiber pollution and how to reduce or eliminate microfibers in clothing. DEEP recently released a report calling for education and awareness campaigns and incentives for internal filters on washing machines (CT DEEP, 2020).

The California state legislature has also *proposed* a number of bills to address microfiber pollution, including three recent bills. AB 2379 (Bloom, 2018) would require clothing made out of 50% or more polyester to include a label stating that the garment sheds microfibers; AB 1724 (Friedman, 2020) would require all state-owned washing machines to contain microfiber filtration; and AB 802 (Bloom, 2021) would mandate the State Water Resources Control Board to identify the best available control technology to filter microfibers from industrial, institutional, or commercial laundry facilities.

Tire and Brake Dust Prevention and Mitigation Policies

As described in *Chapter 2: Microplastics Explained*, tire and brake microplastics are identified as among the most abundant types of microplastics in the environment. They are concentrated near roadways and transportation hubs from which fragments may be further transported through the air and by runoff to distant locales. Additionally, scrap tires are frequently recycled for use on playgrounds, or for athletic turf, which may constitute as an additional source of exposure and release into the environment (EPA, 2022a).

CalSPEC found two national level legislative actions to address recycled tires as a source of microplastic (Table 17), but no actions at other levels of government.

Table 17: National Actions on Microplastics Derived from Tires

Country	Year	Name of Law or Action	Description
Norway	2018	Norwegian Development Program to Combat Marine Litter and Microplastics (Report and Regulations)	Commissioned a review on microplastics pollution, which includes measures to target wear and tear of vehicle tires and textiles and losses from artificial turfs. In 2021 regulations were established against the use of plastic rubber granulate on sports fields, nondegradable plastics and a ban on single-use plastics was enacted.
European Union	2021	EU Regulations on Tire Labeling	Allow current law on tire labelling to be expanded to include the emission of microplastics, once a suitable testing method for measuring tire abrasion is available.

Source: CalSPEC, 2023.

Norway, a country that has the longest coastline in Europe and is economically dependent on the marine environment, produced some of the most advanced and comprehensive research on microplastic release. In 2018, the Norwegian Climate and Environment Ministry commissioned a review of microplastics pollution to measure, among other things, microplastic release from wear and tear of vehicles tires and losses from artificial turfs (Norwegian CEM, 2021). Researchers identified tire abrasion, road dust, and rubber granulate from artificial turf pitches as the largest land-based sources of microplastics. In response to the findings, Norway implemented regulations on July 1, 2021 to reduce the use of plastic rubber granulate on sports fields by 90% (Norwegian CEM, 2021).

The European Union recently presented a proposal to reduce air pollution from new motor vehicles sold in the EU to meet the European Green Deal's zero-pollution goal. The new law would move beyond regulating air pollution (tail pipe vehicle emissions) and would set additional limits for particulate emissions from brakes and microplastic emissions from tires (EC, 2022).

Multinational Agreements Prevention and Mitigation Policies

To date, there have been 12 actions at the multinational level to address microplastics pollution broadly. Perhaps the most comprehensive plastics reduction strategy to date was proposed by the European Union in January 2018. Its intent is to reduce all sources contributing to microplastic pollution. This commitment was renewed with subsequent actions outlined in the European Green deal in December 2019, the new Circular Economy Action Plan in March 2020, and the Zero Pollution Action Plan in May 2021. The latter action seeks to reduce of the amount of microplastics released into the environment by 30% by 2030 (EC, 2021). Each substrategy contains proposed policies that tackle microplastics pollution (particles <5 mm) from primary (e.g., cosmetics, detergents, paints) and secondary sources (e.g., tires and synthetic textiles). The other Table 18 entries primarily focus on resolutions promulgated by the United Nations Environment Assembly, the world's highest-level decision-making body for environmental issues; it is composed of 193 United Nations Member States. These resolutions have no enforcement mechanisms; however, they demonstrate long-standing, global awareness and concern about environmental impacts of microplastics.

Table 18: Multinational Microplastics Agreements

Rulemaking Body	Year	Name of Law or Action	Description
United Nations Environmental Program and NOAA*	2011	Honolulu Strategy	Planning tool, or framework, to improve cooperation to address marine debris broadly, including plastics and microplastics.
United Nations Environment Assembly (UNEA)	2014	Resolution 1/6 Marine Plastic Debris and Microplastics	Encouraged the implementation of the Honolulu Strategy, including defining the problem of "marine plastic debris and microplastics," and required research to further understand the impacts.
UNEA	2016	Resolution 2/11 Marine Plastic Litter and Microplastics	The Resolution calls for better understanding of the impacts of marine debris (plastics and microplastics), develop best practices to prevent its and minimize its levels in the marine environment, encourages Member States to further develop partnerships with industry and civil society to raise awareness of the extent of the impact of marine debris on the biological diversity, health, and encourages member States to cooperate to address marine debris and microplastics in the marine environment.
United Nations General Assembly (UNGA)	2016	Action on Oceans and the Law of the Sea	Calls for better understanding of the impacts of marine debris (plastics and microplastics), develop best practices to prevent its and minimize its levels in the marine environment, encourages Member States to further develop partnerships with industry and civil society to raise awareness of the extent of the impact of marine debris on the biological diversity, health, and encourages member States to cooperate to address marine debris and microplastics in the marine environment.
Conference of the Parties (COP) Basel Convention	2017	13/17 Work program and operations of the open-ended working group	Consider relevant options available under the Convention to further address marine plastic litter and microplastics, taking into account, the assessment requested by the United Nations Environment Assembly of the United Nations Environment Program in its resolution 2/11.
UNEA	2018	Resolution 3/7 Marine Litter and Microplastics	Urges states to reduce plastic pollution and prioritize cleanup of land-based sources of plastics leaking into the ocean, both macro and microplastics. The main instrument recommended is to urge states to develop national action plans that address plastic pollution at all stages of the life cycle.

Rulemaking Body	Year	Name of Law or Action	Description
UNEA	2019	Resolution 4/7 Environmentally Sound Management of Waste	Invites states to “reduce microplastics, including in wastewater treatment plants, and encourage producers to use alternatives to microbeads.”
UNEA	2019	Resolution 11 Protection of the Marine Environment from Land-Based Activities	Member States agree to enhance the mainstreaming of the protection of coastal and marine ecosystems in policies, particularly those addressing environmental threats caused by marine litter and microplastics.
UNEA	2019	Resolution 4/6 Marine Litter and Microplastics	Requests UNEP to provide information on sources, pathways, and hazards of litter, including plastic litter and microplastics pollution; indicators to harmonize monitoring, reporting, and assessment methodologies; guidelines for the use and production of plastics in order to inform consumers; and, any information to inform policies and action.
Conference of the Parties (COP) Basel Convention	2019	14/13 Further actions to address plastic waste	Calls upon parties and others to promote environmentally sound and efficient management of plastic waste to reduce the discharge of microplastics.
UNEA	2022	Resolution 5/11 End Plastic Pollution: Towards an international legally binding instrument	Establishes a commitment to forge a legally binding agreement by the end of 2024 to end plastic pollution (including microplastics), as well as addressing the full lifecycle of plastic, including its production, design, and disposal.
European Union	2021	Zero Pollution Action Plan	Proposes a requirement to reduce plastic litter at sea by 50%, and microplastics by 30%.

Source: CalSPEC, 2023.

The multinational focus on plastic pollution began in 2011 at the Fifth International Marine Debris Conference, where the United Nations Environmental Program (UNEP) and the United States National Oceanic and Atmospheric Administration (NOAA) developed the Honolulu Strategy as a planning tool to improve cooperation on marine debris pollution broadly, including plastics. The Honolulu Strategy was also intended to be used as a monitoring tool on multiple levels—global, regional, national, and local — involving civil society, government and intergovernmental organizations, and the private sector.

Following release of the Honolulu Strategy, the United Nations Environment Assembly (UNEA) convened several times to discuss multinational policies to reduce plastic pollution, including microplastics specifically, through nonbinding resolutions.

- In 2014, the UNEA adopted “Resolution 1/6” defining the problem of plastic pollution as “marine plastic debris and microplastics," the first multinational focus on microplastics policy. Resolution 1/6 also required a report, eventually titled: "Marine Plastic Debris and Microplastics Global Lessons and Research to Inspire Action and Guide Policy Change."[10]

- In 2016, the UNEA shared the results from the report required by Resolution 1/6 and adopted Resolution 2/11, which focused for the first time on microplastics by encouraging "manufacturers to consider impacts of products containing microbeads … and eliminate or reduce the use of primary microplastic particles in products." In 2018, Resolution 3/7 passed, which recommended adoption of national plans to address the full life cycle of plastic pollution, including microplastics. In 2019, the UNEA began to address specific aspects of microplastics and adopted Resolutions 4/7, 11, and 4/6[11]. In 2022, the UNEA passed Resolution 5/11 which moves toward a legally binding document to end all plastic pollution (explicitly including microplastics) by addressing the full life cycle of plastic — its production, design, and disposal. The first meeting of a multinational negotiating committee occurred in November 2022 in Uruguay with a goal to draft an agreement by 2024.

Concurrently, there were separate but related efforts during the United National General Assembly (UNGA) and the Conference of the Parties Basel Convention (COP Basel Convention). In 2016, UNGA's report "Oceans and the Law of the Sea" recognized the need to understand the sources, amounts, pathways, distribution, impacts and trends of marine debris, especially plastics and microplastics and called upon member states to implement Resolution 2/11. UNGA also called on member states to develop partnerships with industry to raise awareness of the impact on biological diversity, health, and productivity of marine debris and microplastics. During the 2019 COP Basel Convention, there were calls to member governments to reduce transboundary movement of plastic waste, consistent with environmentally sound and efficient management, and to reduce the discharge of plastic waste and microplastics.

Evaluating Policy Effectiveness

Policy evaluations are important tools for measuring policy outcomes such as goal attainment, program effectiveness, intended and unintended effects, and costs. They help ensure transparency, accountability, and stewardship of resources. Evaluations apply a set of rigorous empirical evaluation principles and methods to examine the implementation and impact of a policy instrument (e.g., laws, bans, regulations).

In this final section, CalSPEC sought studies that measured the quantitative impact of policies on concentrations of microplastics in the environment or that assessed the cost-effectiveness of such

CalSPEC found no studies evaluating the impact of policies on microplastic concentrations or reduction efforts.

[10] The 2016 Report (titled *Marine Plastic Debris and Microplastics: Global Lessons and Research to Inspire Action and Guide Policy Change)* findings justified a call to action, especially on the problem of "marine plastic litter," and identified methods (e.g., protocols, sampling) to address to all stages of the life cycle of plastic products and the need for consumers behavior change.

[11] Most notably, Resolution 4/6 requested the expert group established previously to take stock of existing activities and actions by governments, regional and global instruments, international organizations, the private sector, and nongovernmental organizations; identify technical and financial resources or mechanisms to address marine plastic litter and microplastics; and to assess effectiveness of response options.

policies.[12] While citations from 2000 to 2022 were emphasized, there were no date restrictions to these search methods. Retrieval of materials was limited to English-language materials.

In the absence of evaluations of microplastics policy effectiveness or impact, CalSPEC conducted an informal search for examples of policy evaluations aimed at *macro*plastics. CalSPEC found two examples of policy evaluations and one survey addressing the actual or modeling effectiveness of macroplastics policies (Table 19). *These macroplastic studies are highlighted because they suggest how microplastics policy evaluations might be framed and conducted*.

Table 19. Policy Evaluations of Macroplastics (Plastic Bag and Beverage Container) Policy Interventions

Policy/Experimental Intervention	Program	Description
Plastic Bag Ban	Australian Capital Territory (ACT) Plastic Bag Ban Lessons	Researchers examined the effect of a plastic bag ban in ACT over a seven-year period and assessed whether or not the ban had reduced plastic bag consumption and litter.
Payment in-lieu of Plastic Bag	University of Kentucky Token Plastic Bag Quasi-Experiment	Researchers examined the effect of a voluntary token donation program, which gave the consumer the opportunity to take part in a small charitable donation in lieu of a plastic bag.
Plastic Bag and Plastic Bottle Ban	Behavior Analysis of Disposed Single-Use Plastic Items in Northwest Ohio Lake Erie Basin	Researchers found two types of debris in the Lake Erie Basin — plastic bags and plastic water bottles — and wanted to survey respondents on the disposal of these plastic items and recommendations on how to positively change behavior to reduce improper disposal.

Source: CalSPEC, 2023.

The first study evaluated the impact of a plastic bag ban in the Australian Capital Territory (ACT). The ban was introduced in 2011 and researchers studied the policy's impacts over a seven-year period. The results suggest the ban reduced consumption of single-use conventional polyethylene bags by approximately 2600 tons (Macintosh et al., 2021). However, these reductions were largely offset by increases in the consumption of other more rigid and durable plastic bags. The net effect of the ban on plastic consumption over the period was relatively minor, only a 275-ton reduction. Additionally, the researchers found that the ban is largely supported by ACT consumers. When the ban was first introduced, 58% of the community supported the ban. By 2018, community support increased by 68%.

A second study, conducted at the University of Kentucky, examined the impact of a voluntary token donation program, which gave consumers the opportunity to direct a small charitable donation in lieu of using a plastic bag. The program resulted in a 30%–40% decrease in bag use (Penn et al, 2022).

[12] Multiple databases were utilized in the literature review process including Ovid MEDLINE (All MEDLINE file), Embase, Nexis Uni, HeinOnline, PAIS, CABI Global Health, Google Scholar, and Scopus. Scopus provided the majority of the results. Search methods included the use of subject headings, keywords, and citation-based searching. Keywords included microplastics, nanoplastics, plastic, particle size, public policy, pollution policy, evidence-based policy, governance, legislation, treaty, agreement, and plural versions of the terms.

In the third study (a behavior analysis), researchers found two types of debris in the Lake Erie Basin (plastic bags and plastic water bottles) and surveyed respondents on the disposal of these plastic items and opinions on how to positively change behavior to reduce improper disposal. Results show strong support for a ban on these items, with more enthusiasm for a bag ban over a plastic bottle ban (Bartolotta, 2018).

Policy Gaps

Microplastics Research

Most legislative and regulatory agency definitions of "microplastics" include specific criteria for particle dimensions; however, as noted in *Chapter 2: Microplastics Explained*, there is no standard scientific definition. Moreover, a gap remains regarding standard definitions of other key concepts such as exposure measurement methods and units, risk assessment methods, and material composition, all of which are important to measuring the comparable effectiveness of policies (SWRCB, 2020). A national or international conference could help to align divergent measures and definitions.

Examples of other research gaps identified among policy reports reviewed by CalSPEC include:

- The impact of paint-derived microplastics;
- The impact of microplastics on air quality and human lung function;
- Optimal microfiber filtration standards for clothes driers;
- Effectiveness of labeling requirements to identify polymers and additives as needed to improve plastic recycling and understand of toxicity of plastics exposure;
- Options to increase ability of public storm water systems to capture macro and microplastics;
- Optimal design for abrasion wear and polymer/additive composition standards for tires;
- Economic and health impacts of a ban on PVC in building materials and furnishings, and expanded-polystyrene plastic packaging;
- Impact of tire and brake dust exposure on health in minority and low-income communities near freeways and freight transportation centers;
- Effectiveness of and options to expand producer responsibility requirements to synthetic clothing, plastic packaging, and other products;
- Impacts of microplastic additives (e.g., bisphenols, phthalates and brominated flame retardants) on human health; the interactions between microplastics and chemical additives control options (e.g., the effectiveness of PFAS emission controls to reduce microplastics in waste water biosolids).

Microbead Prevention and Mitigation

Although there has been significant action on microbeads recently, it is not clear how effective these policies are. More research is needed to assess the efficacy of these programs and to ensure that industries are complying with current laws. Overall, efforts to address the release of microbeads into the environment has been a first step to understanding the full life cycle of one source of microplastics.

> Proposed legislation, AB 2787 (Quirk, 2022) would have expanded California's microbead statewide ban to include microplastics that are not subject to AB 888 law, such as microbeads intentionally added to leave-on products, and personal cleaning products that do not wash-off (e.g., face lotions). The proposed law would have also banned detergents, waxes, and polishes containing microbeads.

Microfiber Prevention and Mitigation

California currently lacks a comprehensive program that addresses textile-related waste. Additional research is needed to assess the efficacy of producer responsibility (e.g., programs in place to take back used clothing); requirements for product reformulation (e.g., shedless textiles); development of and adoption of filtration technologies; and legislation to educate public on benefits of non-plastic textiles. These areas could be explored as avenues for future legislation.

Prevention and Mitigation of Tire-derived Microplastics

California currently lacks a comprehensive program to measure tire-derived microplastic concentrations in ambient air and to quantify microplastic components of fine particulate matter (PM2.5). In addition, more research is needed on tire reformulation, on-board tire/brake dust capture systems, optimized street sweeping systems (particularly in high-impact residential areas near freeways and transportation hubs) and enhanced producer responsibility for used tires. California's Statewide Microplastics Strategy calls for developing a tires-specific pollution prevention strategy by 2023 (OPC, 2022).

Multinational Policies

Current international actions are not legally binding and only offer guidance, recommendations, and strategies for future actions. But it is possible that a multinational agreement emerging from UN Resolution 5/11 could include some enforceable measures, such as caps on total production of the most health damaging polymers/additives, or labeling requirements. California could potentially participate in these multinational negotiations (the first of five meetings was held in Uruguay in November 2022) on plastics policies, as observers, content experts and advisors to US governments participants, with a goal to secure enforceable provisions and globalize California research and policies.

Policy Evaluations

Although the three studies reviewed in this report have only indirect applicability to microplastics, they do provide "proof of concept" for more rigorous efforts to study environmental and consumer behavior impacts of microplastic policies. There is a strong need for empirical policy impact evaluations; environmental and economic impact modelling; and randomized controlled policy experiments focused on different microplastics policy interventions.

Separately, there is very little California-specific research that has been conducted measuring the economic damage of microplastics. CalSPEC found one report that estimated the ecological and health impacts of microplastics to be between $3,300 and $33,000 per ton of microplastics entering a specific marine environment in France based on numbers that were described as "conjecture." This is a good example of the current state of microplastics valuation research and suggests the need for additional research to identify fiscal and economic impacts, which is necessary to conducting future cost benefit analyses of specific regulatory policies (Beaumont et al., 2019).

Microplastics Policies: Summary and Conclusions

This chapter describes actions taken by multinational, national, and state/provincial governments since 2010 to reduce the prevalence of microplastics. In sum, there are 51 policies directed at reducing microplastics in the environment. Initial efforts focused on banning microbeads in cosmetics. More recently, policy efforts have focused on microplastic fibers (e.g., washing machine filtration in France) and degradation of tires (e.g., restrictions on use of recycled tires on Norwegian sports fields).

Multinational rulemaking bodies have begun to act on microplastics and are actively working to establish a legal framework to bind member states to a set of targets, mandates, and metrics.

National and subnational governments are beginning to realize the scale and impact of microplastics associated with microplastic degradation and multinational transport through land, water, air, and living things (biota). While some states have allocated funding to reduce microplastics exposure through enhanced measurement standards and regular testing requirements, many research gaps remain. Most national and state governments are still working to understand how best to reduce current levels of microplastics, and how to establish methods or technologies to replace source materials that release or break down into microplastics in the environment. The most comprehensive work on microplastic research needs is reflected in the Ocean Protection Council's February 2022 Statewide Microplastic Strategy.

Lastly, no empirical evaluations exist to assess the impact of the legislative actions described above. CalSPEC identified three empirical evaluations on the impact of macroplastic (mainly plastic bag) policies and interventions, which are presented only as examples of approaches policy researchers might take with respect to microplastics. This suggests a need for additional research on monetary value of microplastic impacts, control/abatement costs and unintended social/economic consequences of microplastic policy actions.

CHAPTER 5: REPORT CONCLUSION

Plastics are slowly degrading fossil fuel–based polymers that are both a core feature of modern life and a major source of environmental pollution, including climate change. Public awareness of plastics pollution, stimulated by news of the Great Pacific Garbage Patch, is shifting to concern about the smaller, less visible particles called microplastics.

This CalSPEC report is intended to provide the California State Assembly Natural Resources Committee and the Senate Environmental Quality committees with scientific evidence on the occurrence of microplastics in the environment, the possible human health effects of microplastics, and the range of public policies that have so far been applied to prevent or mitigate microplastics pollution.

Key Findings: Environment

There is substantial evidence that microplastics are ubiquitous in the environment. Although research in this arena is nascent, microplastic particles have been found in substantial concentrations in every environmental compartment where they have been studied: in land, water, air; in arctic glaciers and deep-sea sediment; in plants and animals; and — within humans — in blood, breast milk, digestive tract, lungs, and skin. Secondary microplastics, estimated to contribute about two-thirds of the total microplastics burden, come from degraded macroplastics such as plastic bags, bottles, utensils, containers, tires, and textiles. Primary microplastics manufactured for direct use (e.g., pellet feedstock for large plastic products and microbeads for industrial, cleaning, and personal care products) are thought to comprise the remaining burden. This has important policy implications because efforts to curtail production or egress of both microplastics and macroplastics into the environment will ultimately influence the prevalence and concentration of microplastics.

Key Findings: Human Health

CalSPEC performed a rapid systematic review (rapid review) of the published literature on the human health effects of microplastics. Because CalSPEC found no human studies, the review was limited to rodent studies (mice and rats), which are routinely used by regulatory agencies to estimate potential human harms. Harms were considered in three organ systems relevant to humans: digestive, reproductive, and respiratory. Of 1,815 articles identified and screened, 24 experimental studies in rodents met the rapid review inclusion criteria. Thirteen studies (7 digestive, 6 respiratory) were fully evaluated for quality and strength of the evidence. Evaluation of study quality is an important component of the CalSPEC process, as it ensures a robust and less biased evaluation of the evidence. Evaluation of the strength is important as it allows CalSPEC to make a hazard conclusion about the effects of exposure to a contaminant on human health.

Based on rigorous evaluation of the evidence for endpoints of the digestive and reproductive systems of rodents, CalSPEC concluded that microplastics are suspected to be a hazard to the human reproductive and digestive systems. Compared to unexposed control groups, rodents exposed to increasing concentrations of microplastics exhibited increasing perturbations of important biological mechanisms (such as inflammation, oxidative stress, and hormone pathways) and of higher-level endpoints (such as anatomic changes in the colon and decreased male sperm counts). Respiratory studies meeting inclusion criteria (but not undergoing the same rigorous review process) had similar directional findings, indicating likely adverse effects to the respiratory system and bolstering CalSPEC's conclusion of suspected human health hazards.

Key Findings: Policy

Of the 51 microplastic actions taken by government entities, 20 ban or curtail the sale or manufacturing of certain products containing microbeads; 11 focus on microplastics research mandates; 6 focus on studying and/or mitigating microfiber release (primarily to waterways); and 2 focus on measuring microplastics emissions from tires abrasion and banning use of plastic rubber granules on sports fields. The remaining 12 actions are multinational agreements that generally call for further microplastics research, development of best management practices, and education. The majority of these agreements focus on the marine environment only.

California has been a national and international leader in developing microplastics mitigation policies through passage of bills banning microbeads, establishing drinking water testing, developing a statewide microplastics strategy, enhancing recycling and composting requirements, and phasing out single-use plastics and plastic packaging. Other jurisdictions have introduced additional policy levers. For example, France has mandated a phase-in of microfiber filters in washing machines, and Norway has banned manufacture of nonbiodegradable plastics, single-use plastics, and limited the use of plastic rubber granules on sports fields.

Many policy opportunities remain. Examples include: optimizing storm water capture systems for both microplastics and macroplastics; measuring tire/brake-derived microplastic concentrations in ambient air and quantifying microplastic components of fine particulate matter (PM2.5); capping production (or sale) of the most health-damaging polymers/additives; and expanding "take-back" producer responsibility requirements on synthetic clothing and plastic packaging.

Finally, there is an absence of policy evaluations on the environmental and economic impact of laws and regulations addressing microplastics. The lack of evaluations may inhibit policy actions and the development of best practices for microplastics prevention and mitigation.

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This report renders three principal conclusions. First, knowledge about microplastics prevalence, distribution, and toxicity to humans is incomplete. Second, despite these knowledge gaps, existing evidence raises concerns about the environmental and health consequences of microplastics pollution. Third, the international community has only just begun to implement policy interventions designed to curtail microplastics pollution, but the effectiveness of these interventions is unknown.

California can act on two fronts simultaneously. More research is clearly needed, beginning with development of standardized measures, more widespread environmental sampling across all environmental compartments, and geographic modeling (leading, for example, to accurate predictions about the extent to which microplastics produced in one location could end up in another). Together, these studies would better characterize the prevalence and distribution of microplastic contaminants. With respect to human health, systematic review, and evidence evaluation of the existing literature on endpoints not covered in this report would add additional knowledge; research is needed on other mammalian species, human *in vitro* studies (cells in test tubes), and human epidemiologic studies (examining, for example, the correlation of microplastics concentrations in blood or tissue with biomarkers for inflammation, oxidative stress, or reproductive reserve). While responsibility for funding most scientific research falls to the federal government, California could spur research in this area by funding pilot projects at California universities, perhaps modeled after the Tobacco-Related Diseases Research Program or the new UC Climate Action Research Initiative.

At the same time, the precautionary principle suggests that California should consider advancing policies that limit microplastic exposure. Some degree of urgency is warranted both because of the long lead time required to reduce (micro)plastic pollution and the long half-life (measured up to centuries) of plastic pollutants. As policies are implemented, it is vital that rigorous research be conducted to quickly identify the policies that are the most effective and efficient at reducing microplastics contamination, at what cost, and with what tradeoffs. Some of the needed information can be derived from economic modelling studies, but policy evaluations using strong cluster-randomized or quasi-experimental designs are also needed.

APPENDIX A HEALTH EFFECTS CHAPTER PROTOCOL AND CONVERSION DETAILS

Microplastics Rapid Review Protocol

This publicly available protocol outlines the process for this rapid systematic review (abstract may be found here). Developing a protocol prior to initiating a review is an important step in a systematic review as it increases transparency in the methods used and reduces the potential for bias. Available on Open Science Framework website at https://osf.io/cwu87.

Rodent-to-Human Exposure Comparison Details

CalSPEC compared the microplastic exposure concentrations in the mouse studies to the predicted exposure concentrations in humans. For this comparison, CalSPEC converted all microplastic concentrations to particles/L for water or particles/g for food. Assuming an approximate daily consumption rate of 5 mL of water and 5 g of food for each mouse, a daily microplastic consumption rate was estimated (Bachmanov et al., 2002). To convert the units from mass to particles, CalSPEC assumed a spherical shape and density of each plastic polymer at standard conditions (1.05 g/cm^3 for polystyrene and 0.96 g/cm^3 for polyethylene).

For microplastic sizes between 5 and 150 μm, the range of daily microplastic intake for the exposed rodent groups is approximately 7 to 70,000 microplastic particles, which is in range with the estimated daily microplastic intake for humans (~422 particles per day; refer to *Chapter 2: Microplastics Explained*) (Zhang et al., 2020). For smaller microplastic sizes such as 0.1 to 0.5 μm, the range of daily exposure concentrations was about 7 x 10^6 to 9.1 x 10^{10}, which could be higher than estimated human exposure concentrations, but more studies are needed to investigate relevant microplastic exposure concentrations and size range.

APPENDIX B HEALTH EFFECTS CHAPTER SUMMARY OF EVIDENCE

Appendix B.1 Full Text Exclusions Rationale: This document outlines the 111 studies that were excluded after reviewing the full text along with rationale for their exclusions. Available at

Appendix B.2 Table of Study Characteristics: This spreadsheet contains information about all the studies from which data was extracted. Available at

Appendix B.3 Table of Results: This spreadsheet contains information about study results for the digestive (n=7) and reproductive (n=6) studies that exposed their test subjects (rodents) to multiple concentrations of microplastics. Available at

Narrative Summary of Evidence

CalSPEC narratively assessed the following outcomes but did not fully evaluate the evidence. Overall, these outcomes were supportive of CalSPEC's conclusions and added confidence in the overall ratings.

Reasons for exclusion of Key Characteristics for digestive studies: Time constraints and many genetic alterations and expressions can be directly or indirectly impacted by microplastic exposure. There is also not a clear interpretation of the role and function of every single gene expression. These are also mostly related to other key characteristics such as apical endpoints and cell proliferation/cell death. Although CalSPEC recognizes there are epigenetic alterations and DNA instability, the team was not confident on interpreting the overall effect, and thus did not evaluate these key characteristics.

Reasons for exclusion of Key Characteristics for reproductive studies: Due to time constraints, CalSPEC prioritized full evaluation of apical outcomes and hormones over other biological changes.

Narrative Summary of Remaining Digestive Key Characteristics

Outcome 1: Alterations in DNA repair or genomic stability

One study (Choi et al., 2021b) looked at the regulation of the signaling pathway of mAChRs in the mid-colon. The expression levels of multiple signaling proteins significantly changed ($p < 0.05$). The same study found significant changes in the MAPK/NF-κB signaling pathway that is involved in regulating the AQP transcription levels. This includes significant increase of the expression and phosphorylation levels of ERK, p38, NF- κB, and IκB ($p < 0.05$).

Outcome 2: Induction of epigenetic alterations

Multiple studies found different epigenetic alterations between control and exposed groups. Two major proteins for mucus secretion, Muc-1 and Muc-2, were measured in the colon and small intestine in five studies. Two studies found contradictory results in fold change of Muc-2 in the colon ($p < 0.05$ down [Wen et al., 2022], $p < 0.005$ up). Three studies found significant decrease of Klf4 mRNA expression levels, gene-associated with mucin secretion ability, in the colon ($p < 0.05$

[Choi et al., 2021b], $p < 0.05$ [Jin et al., 2019], $p = 0.0271$ [Lu et al., 2018]). All other studies (Choi et al., 2021b; Jin et al., 2019; Lu et al., 2018) found significant decrease in relative mRNA expression levels in the colon for Muc-1 and Muc-2. One study (Djouina et al., 2022) investigated multiple protein expression markers, including Vil1, ChgA, Lgr5, Ocln, and F11r in colon, proximal intestine, and distal intestine. The colon induced the highest significant changes for Vil1 ($p < 0.01$ up), ChgA ($p < 0.005$ up), Ocln ($p < 0.01$ up), and F11r ($p < 0.01$ up) (Mann-Whitney nonparametric U test). Wen et al. (2022) also looked at Ocln in the colon but found a contradictory result with (Djouina et al., 2022) ($p < 0.001$ down, one-way analysis of variance). Djouina et al. (2022) also found a significant decrease of Ocln expression level in the distal intestine ($p = 0.04$) but no significant change in the proximal intestine. One study (Choi et al., 2021b) found significant decrease in mRNA levels of genes related to chloride ion transport and water transport in colon (CFTR, CIC -2, AQP3, AQP8) ($p < 0.05$, one-way analysis of variance. The last study (Jin et al., 2019) found significant decrease for multiple mRNA levels of different genes in the colon in the exposed group compared to the control (Retnlb, Cftr, SLC26A6, nkcc1, Nhe3, and CFTR protein; $p < 0.05$, one-way analysis of variance).

Narrative Summary of Remaining Reproductive Key Characteristics

Outcome 1: (Male) Alters germ cell development, function, or death OR alters somatic cell development, functions, or death; (Female) Alters survival, proliferation, cell death, or metabolic pathways

There were multiple studies focusing on this outcome. Three studies (B Hou et al., 2021; Jin et al., 2022; Li et al., 2021) focused on male reproductive health tested for sperm count, sperm deformity (also can be defined as abnormality or malformation), and testicular and epididymal organ coefficients (defined as organ weight divided by body weight). The three studies found a significant decrease of the rate of living sperm and sperm deformity in the testis ($p < 0.05$, one-way analysis of variance and t-test). A fourth study (Huang et al., 2022) also found a significantly reduced sperm count in the epididymis ($p < 0.05$, one-way analysis of variance). One study (Jin et al., 2022) found a significant decrease in the epididymal organ coefficient ($p < 0.01$, one-way analysis of variance) while two studies (B Hou et al., 2021; Jin et al., 2022) found a significant decrease in the testicular organ coefficient ($p < 0.05$, one-way analysis of variance and t-test). Apoptosis was also tested in three studies using two types of staining methods and found significant difference in the exposed groups in the testis (B Hou et al., 2021; Li et al., 2021) and ovaries (An et al., 2021) ($p < 0.05$. one-way analysis of variance). One study found significant alterations to the testis, including seminiferous tubular diameter and germinal epithelium thickness ($p < 0.01$, t-test).

Outcome 2: Induction of epigenetic changes

Four studies found significant epigenetic changes in the exposed groups compare to the control. One study (An et al., 2021) found significant changes in the protein expressions for biomarkers in Wnt/β-catenin signaling pathway, which plays a key role in cell proliferation, differentiation, and apoptosis ($p < 0.05$, one-way analysis of variance). The second study (Jin et al., 2022) observed significant changes in the five protein levels that correlate with testosterone synthesis in testis tissue ($p < 0.05$, t-test). The third study found significant changes in the expression of four blood-testis barrier (BTB) (broad-complex, tramtrack, and bric-a-bric) proteins in the testis ($p < 0.05$, one-way analysis of variance) (Li et al., 2021). The last study (J Hou et al., 2021) observed significant changes in the expression of seven out of ten biomarkers related to the NLRP3/Caspase-1 signaling pathway in the ovaries.

Outcome 3: Induction of oxidative stress

Four studies investigated the significant concentration changes of markers related to oxidative stress. Two studies found significant changes in malondialdehyde and superoxide radical concentration in the testis (Huang et al., 2022; Li et al., 2021) and the ovaries (An et al., 2021; J Hou et al.,) each ($p < 0.05$ one-way analysis of variance). Two studies found significant changes for catalase and glutathione peroxidase concentration in the testis (catalase [Huang et al., 2022] and glutathione peroxidase [Li et al., 2021]) and ovaries ($p < 0.05$, one-way analysis of variance) (An et al., 2021; J Hou et al., 2021).

Outcome 4: (Male) Induction of inflammation

Two studies investigated inflammatory markers in the testis. One study (B Hou et al., 2021) found significant changes in IL-1β, IL-6, TNF-α, Nrf2, and HO-1/β-actin expression levels ($p < 0.05$, one-way analysis of variance). The second study (Li et al., 2021) also found a significant decrease for Nrf2 expression levels in the testis ($p < 0.05$, one-way analysis of variance). Lastly, one study found significant changes in IL-1β concentrations in serum (J Hou et al., 2021).

Outcome 5: (Male) Alters DNA repair or causes genomic instability

One study (B Hou et al., 2021) found significant changes in IκBα, p-IκBα, NF-κBp65, and p-NF-κBp65 expression levels ($p < 0.05$, one-way analysis of variance).

APPENDIX C HEALTH EFFECTS CHAPTER EVIDENCE EVALUATION DETAILS

A Note on Prioritization of Evaluated Outcomes (Table 9)

As indicated in Table 9 in the text of the report, CalSPEC excluded the evaluation of certain key characteristics. There are many genetic alterations and expressions that can be directly or indirectly impacted by microplastic exposure. There is also not a clear interpretation of the role and functionality of every single gene expression. They are also mostly related to other key characteristics such as apical endpoints and cell proliferation/cell death. Although CalSPEC wants to recognize there are epigenetic alterations and DNA instability, CalSPEC is not confident on interpreting the overall effect, and thus did not evaluate these key characteristics.

CalSPEC also did not include studies that measured testicular damage by organ weight, as CalSPEC made the prespecified decision to not include outcomes related to organ weight. CalSPEC prioritized sperm related outcomes, testicular damage, and hormones over organ coefficients (measure of organ weight) and body weight. Organ coefficients and body weight are of less relevance.

Ratings & Justifications

Appendix C.1 is a document describing the risk of bias ratings and justifications for the studies. Risk of bias assessments are done for each individual study. There are seven domains that must be rated, and the possible ratings are low, probably low, probably high, or high. This appendix contains the ratings (with justifications) for the seven digestive studies and six reproductive studies included in the evaluation of the evidence. The risk of bias ratings are then used in the evaluation of study quality, which informs the strength of the evidence rating. See below for summary heat maps on risk of bias.

Risk of Bias Heat Maps

Table 20. Risk of Bias Heat Map for Digestive Studies

	Sequence Generation	Allocation Concealment	Blinding of Personnel & Outcome Assessors	Incomplete Outcome Data	Selective Outcome Reporting	Conflicts of Interest	Other Potential Threats to Validity – Outcome Evaluation	
Jin et al., 2019	+	-	-	++	+	+	+	
Lu et al., 2018	+	-	-	++	+	+	+	
B. Li et al., 2020	-	-	-	++	+	++	+	
Choi et al., 2021a	-	-	-	-	+	++	+	
Choi et al., 2021b	-	-	-	-	+	++	+ (n=1)[a]	- (n=5)[b]
Djouina et al., 2022	+	-	-	+	+	++	+	
Wen et al., 2022	+	-	-	+	+	++	+ (n=2)[c]	- (n=5)[d]

Source: CalSPEC, 2023

Notes: ++ indicates low, + indicates probably low, - indicates probably high, -- indicates high.

a) Modulates receptor-mediated effects: CCK concentration, Gastrin concentration (mid colon)

b) Mucosa thickness, Muscle thickness, Flat luminal surface thickness, Crypt layer thickness (mid colon), charcoal transit ratio (mid colon); Intestine length (mid colon); Alters cell proliferation, cell death, or nutrient supply: Number of crypt of Lieberkuhn (mid colon); Alters cell proliferation, cell death, or nutrient supply: Goblet cell counts (mid colon)

c) Colon length; Induces chronic inflammation: Pro-inflammation cytokines (TNF-α, IL-6, and IL-10)

d) Alters cell proliferation, cell death, or nutrient supply: Goblet cell counts; Oxidative stress: Colonic glutathione (GSH); Oxidative stress: Superoxide dismutase (SOD); Oxidative stress: Malondialdehyde (MDA); Muscular layer width, Crypt depth (colon), intestine (proximal)

Table 21. Risk of Bias Heat Map for Reproductive Studies

	Sequence Generation	Allocation Concealment	Blinding of Personnel & Outcome Assessors	Incomplete Outcome Data	Selective Outcome Reporting	Conflicts of Interest	Other Potential Threats to Validity – Outcome Evaluation	
An et al., 2021	+	-	-	+	+	++	+ (n=1)[a]	- (n=1)[b]
J Hou et al., 2021	+	-	-	+	+	++	+ (n=1)[c]	- (n=1)[d]
Huang et al., 2022	+	-	-	+	+	++	-	
B Hou et al., 2021	+	-	-	++	+	++	- (n=1)[e]	-- (n=1)[f]
Li et al., 2021	+	-	-	++	+	++	+ (n=1)[g]	- (n=2)[h]
Jin et al., 2022	+	-	+	++ (n=2)[i]; - (n=2)[j]	+	++	+ (n=2)[k]	- (n=2)[l]

Source: CalSPEC, 2023.

Notes: ++ indicates low, + indicates probably low, - indicates probably high, -- indicates high.a) Hormone level changes: AMH levels (ovaries)

b) Follicles/Ovarian reserve capacity: Number of growing follicles

c) Hormone level changes: AMH levels (pg/ml) IL-18 (pg/ml) IL-1β (pg/ml)

d) Follicles: Number of growing follicles

e) Sperm damage: Rate of living sperm (%)

f) Sperm damage: Malformation (%)

g) Sperm damage: Sperm motility (%)

h) Sperm damage: Sperm concentration (106/ml); Sperm Damage: Sperm abnormality (%)

i) Viability of sperm (%); Sperm damage: Sperm abnormalitydeformity (%)

j) Hormone level changes: Testosterone LH levels (ng/ml) FSH levels (ng/ml) Concentrations of testosterone in serum (ng/ml); Testicular Damage: Seminiferous tubular diameter, Germinal epithelium thickness

k) Sperm damage: Viability of sperm (%); Hormone level changes: Testosterone LH levels (ng/ml) FSH levels (ng/ml) Concentrations of testosterone in serum (ng/ml)

l) Sperm damage: Sperm abnormality (%); Testicular Damage: Seminiferous tubular diameter, Germinal epithelium thickness

Additional Details on Methods for Evaluating the Quality and Strength of the Evidence

The rapid review used a multistep process to rate the overall *quality of evidence* for each of the primary digestive and reproductive outcomes and considered different factors that can increase or decrease the confidence in the scientific evidence finding that microplastics exposures can result in harms to the digestive or reproductive system.

Animal studies typically use a study design where animals are deliberately exposed to exposure of interest (in this case, microplastics). This is the same method used in randomized controlled trials (RCTs) of pharmaceuticals for human use (which are considered highest confidence evidence).

Given that these animal studies are similar in experimental design to RCTs, the Navigation Guide[13] and NTP OHAT method[14] start this evidence as "high quality" evidence. The team then considered eight factors to make a judgement on the quality of the evidence. This provides a structured approach to considering these domains and each rating is accompanied by narrative for both individual considerations and overall judgement.

Table 22. Example of Quality of Evidence Evaluation Conclusion

		Example Outcome	
	Criteria	Starting Rating: ***High Quality***	Meaning of Example Rating*
Options: Downgrade or Don't Change	(1) Risk of bias across studies	-	Downgrade ***(high to moderate)***
	(2) Indirectness	0	Don't Change ***(stays moderate)***
	(3) Inconsistency	0	Don't Change ***(stays moderate)***
	(4) Imprecision	0	Don't Change ***(stays moderate)***
	(5) Publication bias	-	Downgrade ***(moderate to low)***
Options: Upgrade or Don' t Change	(6) Large magnitude of effect	0	Don't Change ***(stays low)***
	(7) Dose response	+	Upgrade ***(low to moderate)***
	(8) Confounding minimizes effect	0	Don't Change ***(stays moderate)***
	Final rating	***Moderate Quality***	

Source: CalSPEC, 2023.

*Ratings are adjusted based upon the previous rating. In this example, the risk of bias rating is moderate, so when the next criteria (indirectness) is evaluated and does not change the quality of the evidence based upon reviewers assessment, the rating will remain at moderate.

When evaluating the Quality of the Body of Evidence for each reported outcome, the evidence for animal studies always begins at a "High Quality" rating and a set of criteria is then applied to determine the confidence we have in the body of evidence. The body of evidence can be downgraded (-) or upgraded (+) no more than 2 levels for each criterion. The eight criteria that are evaluated are defined in detail in the protocol, which can be found in Appendix A. The final rating is then translated into "high," "moderate," or "low" quality of evidence. These ratings provide a structured approach to applying expert evaluation of the evidence.

[13] Woodruff, T. J., & Sutton, P. (2014). The Navigation Guide systematic review methodology: a rigorous and transparent method for translating environmental health science into better health outcomes. *Environmental health perspectives*, *122*(10), 1007–1014. https://doi.org/10.1289/ehp.1307175

[14] National Toxicology Program (NTP). (2019). Handbook for conducting a literature-based health assessment using OHAT approach for systematic review and evidence integration. https://ntp.niehs.nih.gov/ntp/ohat/pubs/handbookmarch2019_508.pdf

After the team reached consensus on quality of evidence (high, moderate, or low), they then compared it to the criteria in the Navigation Guide and National Toxicology Program's Office of Health Assessment and Translation (NTP OHAT) systematic review method Hazard Identification Scheme. NTP OHAT Hazard identifications conclusions are initially reached by integrating the highest level-of-evidence conclusion for a health effect(s) from the human and the animal evidence streams. On an outcome basis, this approach applies to whether the data support a health effect conclusion or provide evidence of no health effect (NTP, 2019). Hazard identification conclusions may be reached on individual outcomes or groups of biologically related outcomes, as appropriate, based on the evaluation's objectives and the available data. The five hazard identification conclusion categories (when human evidence is available) are:

1. "Known to be a hazard to humans;"
2. "Presumed to be a hazard to humans;"
3. "Suspected to be a hazard to humans:"
4. "Not Classifiable as a hazard to humans"
5. "Not identified as a hazard to humans" (National Toxicology Program (NTP), 2019).

However, if one evidence stream (either human or animal) is characterized as "Inadequate Evidence" (as there are no available studies), then conclusions are based on the remaining evidence stream alone. Given that there are no available human studies, only three of the NTP ratings could be considered ("Presumed to be a hazard to humans," "Suspected to be a hazard to humans," and "Not classifiable as a hazard to humans"), as the other two require human evidence. Thus, CalSPEC applied these three hazard identification conclusion categories.

Quality of the Evidence Ratings

Appendix C.2 is a spreadsheet that outlines the ratings for the body of evidence by selected outcome for the digestive and reproductive studies.

REFERENCES

Allen S, Allen D, Karbalaei S, Maselli V, Walker TR. Micro(nano)plastics sources, fate, and effects: What we know after ten years of research. *Journal of Hazardous Materials Advances.* 2022;6: 100057. http://doi.org/10.1016/j.hazadv.2022.100057

Akdogan Z, Guven B. Microplastics in the environment: A critical review of current understanding and identification of future research needs. *Environmental Pollution*. 2019;254:113011. https://doi.org/10.1016/j.envpol.2019.113011

American College of Obstetricians and Gynecologists' (ACOG) Committee on Obstetric Practice. Reducing Prenatal Exposure to Toxic Environmental Agents: ACOG Committee Opinion, Number 832. *Obstetrics and Gynecology*. 2021;138(1):e40-e54. https://doi.org/10.1097/aog.0000000000004449

American College of Obstetricians and Gynecologists (ACOG). Exposure to toxic environmental agents. Committee Opinion No. 575. *Obstetrics and Gynecology*. 2013;122(4):931-935. https://doi.org/10.1097/01.AOG.0000435416.21944.54

Amrhein V, Greenland S, McShane B. Scientists rise up against statistical significance. *Nature. 2019;* (7748):305-307. https://doi.org/10.1038/d41586-019-00857-9

An R, Wang X, Yang L, et al. Polystyrene microplastics cause granulosa cells apoptosis and fibrosis in ovary through oxidative stress in rats. *Toxicology*. 2021;449:152665. https://doi.org/10.1016/j.tox.2020.152665

Andrady AL, Neal MA. Applications and societal benefits of plastics. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*. 2009;*364*(1526):1977–1984. https://doi.org/10.1098/rstb.2008.0304

Arzuaga X, Smith MT, Gibbons CF, et al. Proposed Key Characteristics of Male Reproductive Toxicants as an Approach for Organizing and Evaluating Mechanistic Evidence in Human Health Hazard Assessments. *Environmental Health Perspectives*. 2019;127(6):065001. https://doi.org/10.1289/EHP5045

Athey SN, Erdle LM. Are We Underestimating Anthropogenic Microfiber Pollution? A Critical Review of Occurrence, Methods, and Reporting. *Environmental Toxicology and Chemistry*. 2022;*41*(4):822-837. https://doi.org/10.1002/etc.5173

Bachmanov AA, Reed DR, Beauchamp GK, Tordoff MG. Food Intake, Water Intake, and Drinking Spout Side Preference of 28 Mouse Strains. *Behavior Genetics*. 2002;32(6):435-443. https://doi.org/10.1023/A:1020884312053

Baheti P. *How is plastic made? A simple step-by-step explanation.* British Plastics Federation. 2022. Retrieved August 3, 2022, from https://www.bpf.co.uk/plastipedia/how-is-plastic-made.aspx

Bai C-L, Liu L-Y, Hu Y-B, Zeng EY, Guo Y. Microplastics: A review of analytical methods, occurrence and characteristics in food, and potential toxicities to biota. *Science of the Total Environment.* 2022;806(Part_1):150263. https://doi.org/10.1016/j.scitotenv.2021.150263

Bakhshoodeh R, Santos RM. Comparative bibliometric trends of microplastics and perfluoroalkyl and polyfluoroalkyl substances: how these hot environmental remediation research topics developed over time. *RSC Advances*. 2022;12(8):4973-4987. https://doi.org/10.1039/D1RA09344D

Baptista Neto JA, Gaylarde C, da Fonseca EM. Microplastics. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing*; 2020*:1-25. https://doi.org/10.1007/978-3-030-10618-8_17-1

Bar-On YM, Flamholz A, Phillips R, Milo R. SARS-CoV-2 (COVID-19) by the numbers. *Elife*. 2020;9:e57309. https://doi.org/10.7554/eLife.57309

Bartolotta JF, Hardy SD. Barriers and benefits to desired behaviors for single-use plastic items in northeast Ohio's Lake Erie basin. *Marine Pollution Bulletin*. 2018; 127:576–585. https://doi.org/10.1016/j.marpolbul.2017.12.037

Basel Convention, Conference of the Parties. *BC-13/17: Work programme and operations of the Open-ended Working Group for the biennium*. 2017. Retrieved June 15, 2022, from https://www.informea.org/sites/default/files/decisions/basel/UNEP-CHW-COP.13-BC-13-17.English.docx

Basel Convention, Conference of the Parties. *Basel Convention 14/13 Further actions to address plastic waste under the Basel Convention.* 2019. Retrieved June 15, 2022, from http://www.basel.int/TheConvention/ConferenceoftheParties/Meetings/COP14/tabid/7520/Default.aspx

BillTrack50. *Federal and State Legislation Tracker.* Retrieved June 20, 2022, from https://www.billtrack50.com/

Boucher J, Friot D. Primary Microplastics in the Oceans: A Global Evaluation of Sources. Gland, Switzerland: IUCN; 2017. Retrieved December 1, 2022 from: https://portals.iucn.org/library/sites/library/files/documents/2017-002-En.pdf

Bucci K, Tulio M, Rochman CM. What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecological Applications. 2020;*30(2):e02044. https://doi.org/10.1002/eap.2044

California Ocean Protection Council (OPC). *Statewide Microplastics Strategy.* 2022. Retrieved June 9, 2022, from https://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20220223/Item_6_Exhibit_A_Statewide_Microplastics_Strategy.pdf

California Office of Environmental Health Hazard Assessment (OEHHA). *About proposition 65*. 2021. Retrieved August 19, 2021 from https://oehha.ca.gov/proposition-65/about-proposition-65

California State Legislature. *AB 888: Waste management: plastic microbeads.* (Reg. Sess. 2015-2016). Retrieved June 9, 2022, from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB888

California State Legislature. *AJR-4 Basel Convention: ratification.* (Reg. Sess. 2021-2022). Retrieved June 9, 2022, from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AJR4

California State Legislature. *SB 1422 California Safe Drinking Water Act: microplastics*. (Reg. Sess. 2017-2018). Retrieved June 9, 2022, from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1422

California State Legislature. *SB 54 Solid Waste: Reporting, packaging, and plastic food service ware.* (Reg. Sess. 2021-2022). Retrieved June 9, 2022, from https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB54

California State Water Resources Control Board (SWRCB). *Microplastics.* Updated October 19, 2022. Retrieved June 9, 2022, from https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html

California State W California State Water Resources Control Board (SWRCB). *Adoption of definition of 'microplastics in drinking water'.* Resolution no. 2020-0021. Retrieved June 9, 2022, from https://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2020/rs2020_0021.pdf

Campanale CG, Savino S, Massarelli I, Ancona C, Volta V, Uricchio P, Felice V. Microplastics pollution in the terrestrial environments: Poorly known diffuse sources and implications for plants. *Science of the Total Environment.* 2022;*805*:150431. https://doi.org/10.1016/j.scitotenv.2021.150431

Carpenter EJ, Anderson SJ, Harvey GR, Miklas HP, Peck BB. Polystyrene Spherules in Coastal Waters. *Science*. 1972;*178*(4062):749-750. https://doi.org/10.1126/science.178.4062.749

Centers for Disease Control and Prevention (CDC). *Per- and Polyfluorinated (PFAS) Factsheet.* 2022a. Retrieved November 15, 2022, from https://www.cdc.gov/biomonitoring/PFAS_FactSheet.html

Centers for Disease Control and Prevention (CDC), Agency for Toxic Substances and Disease Registry (ATSDR). *What are the health effects of PFAS?* 2022b. Retrieved November 15, 2022, from https://www.atsdr.cdc.gov/pfas/health-effects/index.html

Center for International Environmental Law (CIEL). *Fossil fuels & plastic.* 2017. Retrieved November 15, 2022, from https://www.ciel.org/issue/fossil-fuels-plastic/#:~:text=Just%20as%20the%20world%20begins,plastic%20industries%20are%20deeply%20connected

Chamas A, Moon H, Zheng J, et al. Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*. 2020;8(9):3494-3511. https://doi.org/10.1021/acssuschemeng.9b06635

Chen Y, Leng Y, Liu X, Wang J. Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. *Environmental Pollution*. 2020;*257*:113449. https://doi.org/10.1016/j.envpol.2019.113449

China National Development and Reform Commission. No*tice No. 80 to forbid the use of microbeads in cosmetics products*. (January 16, 2020). Retrieved June 13, 2022, from https://www.ndrc.gov.cn/xxgk/zcfb/tz/202001/t20200119_1219275.html?code=&state=123

Choi YJ, Park JW, Lim Y, Seo S, Hwang DY. In vivo impact assessment of orally administered polystyrene nanoplastics: biodistribution, toxicity, and inflammatory response in mice. *Nanotoxicology*. 2021a;15(9):180-1198. https://doi.org/10.1080/17435390.2021.1996650

Choi YJ, Park JW, Kim JE, et al. Novel Characterization of Constipation Phenotypes in ICR Mice Orally Administrated with Polystyrene Microplastics. *International Journal of Molecular Sciences*. 2021b;22(11);5845. https://www.mdpi.com/1422-0067/22/11/5845

Conesa JA, Iñiguez ME. Analysis of Microplastics in Food Samples. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-16. https://doi.org/10.1007/978-3-030-10618-8_5-1

Congress of the French Parliament. *LAW n° 2020-105 of February 10, 2020, relating to the fight against waste and the circular economy*. (February 10, 2020). Retrieved June 14, 2022, from https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000041553759

Conley K, Clum A, Deepe J, Lane H, Beckingham B. Wastewater treatment plants as a source of microplastics to an urban estuary: Removal efficiencies and loading per capita over one year. *Water Research X*. 2019;*3*:100030. https://doi.org/10.1016/j.wroa.2019.100030

Connecticut Department of Energy and Environmental Protection (DEEP). (2020). *Report to the Legislature on the Findings of the Synthetic Microfiber Working Group*. Retrieved July 21, 2022, from https://portal.ct.gov/DEEP/P2/Microfiber-Pollution

Connecticut General Assembly. *Substitute House Bill No. 5360 Public Act No. 18-181*. (Reg. Sess. 2018) Retrieved June 14, 2022, from https://cga.ct.gov/2018/act/pa/2018PA-00181-R00HB-05360-PA.htm

Conti GO, Ferrante M, Banni M, et al. Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population. *Environmental Research*. 2020;187:109677. https://doi.org/10.1016/j.envres.2020.109677

Corcoran PL. Degradation of Microplastics in the Environment. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-12. https://doi.org/10.1007/978-3-030-10618-8_10-1

Cowger W, Booth AM, Hamilton BM, et al. Reporting Guidelines to Increase the Reproducibility and Comparability of Research on Microplastics. *Applied Spectroscopy*. 2020a;74(9):1066-1077. https://doi.org/10.1177/0003702820930292

Cowger W, Gray A, Christiansen SH, et al. Critical Review of Processing and Classification Techniques for Images and Spectra in Microplastic Research. *Applied Spectroscopy*. 2020b;74(9):989-1010. https://doi.org/10.1177/0003702820929064

Cox KD, Coverton GA, Davies HL, Dower JF, Juanes F, Dudas SE. Human Consumption of Microplastics. *Environmental Science & Technology*. 2019;53(12):7068-7074. https://doi.org/10.1021/acs.est.9b01517

da Costa JP, Duarte AC. Introduction to the Analytical Methodologies for the Analysis of Microplastics. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.). *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-31. https://doi.org/10.1007/978-3-030-10618-8_1-1

Danopoulos E, Twiddy M, Rotchell JM. Microplastic contamination of drinking water: A systematic review. *PLoS One*. 2020a;15(7):e0236838. https://doi.org/10.1371/journal.pone.0236838

Danopoulos E, Jenner L, Twiddy M, Rotchell JM. Microplastic contamination of salt intended for human consumption: a systematic review and meta-analysis. *SN Applied Sciences.* 2020b;2(12):1950. https://doi.org/10.1007/s42452-020-03749-0

Danopoulos E, Jenner LC, Twiddy M, Rotchell JM. Microplastic contamination of seafood intended for human consumption: a systematic review and meta-analysis. *Environmental Health Perspectives*. 2020c;128(12). https://doi.org/10.1289/EHP7171

Dauvergne P. The power of environmental norms: Marine Plastic Pollution and the politics of microbeads. *Environmental Politics*. 2018;(27)4:579-597. https://doi.org/10.1080/09644016.2018.1449090

de Ruijter VN, Redondo-Hasselerharm PE, Gouin T, Koelmans AA. Quality Criteria for Microplastic Effect Studies in the Context of Risk Assessment: A Critical Review. *Environmental Science & Technology*. 2020;54(19):11692-11705. https://doi.org/10.1021/acs.est.0c03057

Desforges JPW, Galbraith M, Ross PS. Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean. *Archives of Environmental Contamination and Toxicology*. 2015;69(3):320-330. https://doi.org/10.1007/s00244-015-0172-5

Djouina M, Vignal C, Dehaut A, et al. Oral exposure to polyethylene microplastics alters gut morphology, immune response, and microbiota composition in mice. *Environmental Research*. 2022;212:113230. https://doi.org/10.1016/j.envres.2022.113230

Dutch Ministry of Infrastructure and the Environment (MIE) and Dutch Ministry of Economic Affairs (MEA). *Marine strategy for the Dutch part of the North Sea 2012-2020*. 2015. Retrieved June 16, 2022, from https://www.noordzeeloket.nl/en/functions-and-use/natuur/@171616/marine-strategy-1/

Eerkes-Medrano D, Thompson RC, Aldridge DC. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research*. 2015;*75*:63-82. https://doi.org/10.1016/j.watres.2015.02.012

Eriksen M, Lebreton LCM, Carson HS., et al. Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLoS One*. 2014;9(12):e111913. https://doi.org/10.1371/journal.pone.0111913

Eriksen MS, Wilson S, Box C, Zellers A, Edwards W, Farley H, Amato S. Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Marine Pollution Bulletin*. 2013;77(1-2):177–182. https://doi.org/10.1016/j.marpolbul.2013.10.007

European Commission (EC). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'*. 2021, December 5. Retrieved August 4, 2022, from https://eur-lex.europa.eu/resource.html?uri=cellar:a1c34a56-b314-11eb-8aca-01aa75ed71a1.0001.02/DOC_1&format=PDF

G7. *Ocean Plastics Charter*. 2018. Retrieved June 14, 2022, from https://www.consilium.europa.eu/media/40516/charlevoix_oceans_plastic_charter_en.pdf%20

Grabiel, T., Gammage, T., Perry, C., & Dixon, C. Achieving sustainable production and consumption of virgin plastic polymers [Policy Brief]. *Frontiers in Marine Science*. 2022;9. https://doi.org/10.3389/fmars.2022.981439

Garritty C, Gartlehner G, Nussbaumer-Streit B, et al. (2021). Cochrane Rapid Reviews Methods Group offers evidence-informed guidance to conduct rapid reviews. *Journal of Clinical Epidemiology*. 2021;*130*:13-22. https://doi.org/10.1016/j.jclinepi.2020.10.007

Gaston E, Woo M, Steele C, Sukumaran S, Anderson S. Microplastics Differ Between Indoor and Outdoor Air Masses: Insights from Multiple Microscopy Methodologies. *Applied Spectroscopy. 2020;*74(9):1079-1098. https://doi.org/10.1177/0003702820920652

Fan Z, Xiao T, Luo H, et al. (2022). A study on the roles of long non-coding RNA and circular RNA in the pulmonary injuries induced by polystyrene microplastics. *Environment International*. 2022;163:107223.

Fan Y, Zheng K, Zhu Z, Chen G, Peng X. Distribution, sedimentary record, and persistence of microplastics in the Pearl River catchment, China. *Environmental Pollution*. 2019*;251*:862-870. https://doi.org/10.1016/j.envpol.2019.05.056

French Ministry of Ecological Transition. *Anti-waste law for a circular economy*. 2021. Retrieved June 14, 2022, from https://circulareconomy.europa.eu/platform/sites/default/files/anti-waste_law_in_the_daily_lives_of_french_people.pdf

Frias J. Sorption of Potentially Toxic Elements to Microplastics. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-16. https://doi.org/10.1007/978-3-030-10618-8_16-1

Gad SE. Polymers. In P. Wexler (Ed.), *Encyclopedia of Toxicology (Third Edition).* Academic Press; 2014:1045-1050. https://doi.org/10.1016/B978-0-12-386454-3.00912-X

Galloway TS, Cole M, Lewis C. Interactions of microplastic debris throughout the marine ecosystem. *Nature Ecology & Evolution*. 2017;1(5):0116. https://doi.org/10.1038/s41559-017-0116

Garritty C, Gartlehner G, Nussbaumer-Streit B, et al. Cochrane Rapid Reviews Methods Group offers evidence-informed guidance to conduct rapid reviews. *Journal of Clinical Epidemiology*. 2021;130:13-22.

Gautam K, Dwivedi S, Anbumani S. Microplastics in Biota. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-23. https://doi.org/10.1007/978-3-030-10618-8_31-1

Geyer R, Jambeck JR, Law KL Production, use, and fate of all plastics ever made. *Science Advances*. 2017;3(7):e1700782. https://doi.org/10.1126/sciadv.1700782

Geyer R. Chapter 2 - Production, use, and fate of synthetic polymers. In T. M. Letcher (Ed.), *Plastic Waste and Recycling*. Academic Press; 2020:13-32. https://doi.org/10.1016/B978-0-12-817880-5.00002-5

Gong J, Xie P. Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics. *Chemosphere.* 2020;254:126790. https://doi.org/10.1016/j.chemosphere.2020.126790

Government of Australia, Department of Climate Change, Energy, the Environment and Water (DCCEEW) *National Plastics Plan.* Updated October 10, 2021. Retrieved June 13, 2022, from https://www.dcceew.gov.au/environment/protection/waste/plastics-and-packaging/national-plastics-plan

Government of Canada. *Canada's Zero Plastic Waste Agenda*. Updated October 31, 2022. Retrieved June 14, 2022, from https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste/canada-action.html

Government of Canada. *Microbeads in Toiletries Regulations (SOR/2017-111).* Justice Laws. Retrieved June 10, 2022, from https://laws-lois.justice.gc.ca/eng/regulations/SOR-2017-111/page-1.html

Government of England. *The Environmental Protection (microbeads) (England) regulations 2017*. Queen's Printer of Acts of Parliament. Legislation.gov.uk. Retrieved June 10, 2022, from https://www.legislation.gov.uk/uksi/2017/1312/contents/made

Government of France. *Decree No. 2017-291 Ban on marketing rinse-off cosmetic products*. Retrieved June 13, 2022, from https://www.legifrance.gouv.fr/loda/id/JORFTEXT000034154540/2022-08-20/

Government of Ontario. *Microplastics and microbeads*. Ontario.ca. Updated August 31, 2021. Retrieved July 6, 2022, from https://www.ontario.ca/page/microplastics-and-microbeads#section-0

Government of New Zealand. *Waste minimisation (microbeads) regulations 2017*. New Zealand Legislation. Retrieved June 13, 2022, from https://www.legislation.govt.nz/regulation/public/2017/0291/latest/DLM7490715.html?search=ts_act%40bill%40regulation%40deemedreg_microbeads_resel_25_a&p=1

Government of Scotland *The Environmental Protection (microbeads) (Scotland) regulations 2018*. Queen's Printer for Scotland. Legislation.gov.uk. Retrieved June 13, 2022, from https://www.legislation.gov.uk/ssi/2018/162/contents/made

Government of Taiwan. *Restrictions on the Manufacture, Import, and Sale of Personal Care and Cosmetics Products Containing Plastic Microbeads*. Environmental Protection Administration, Executive Yuan. 2017. Retrieved June 10, 2022, from https://oaout.epa.gov.tw/law/EngLawContent.aspx?lan=E&id=199&KW=plastic

Government of Wales. *The Environmental Protection (microbeads) (Wales) regulations 2018*. Queen's Printer of Acts of Parliament. Legislation.gov.uk. Retrieved June 13, 2022, from https://www.legislation.gov.uk/wsi/2018/760/contents/made

Government of Ontario *Microplastics and microbeads. Updated August 31, 2021.* Retrieved September 12, 2022, from https://www.ontario.ca/page/microplastics-and-microbeads#section-0

Hale RC, Seeley ME, King AE, Yu LH. Analytical Chemistry of Plastic Debris: Sampling, Methods, and Instrumentation. In M. S. Bank (Ed.), *Microplastic in the Environment: Pattern and Process*. Springer International Publishing; 2022:17-67. https://doi.org/10.1007/978-3-030-78627-4

Halsband C. Effects of Biofouling on the Sinking Behavior of Microplastics in Aquatic Environments. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-13. https://doi.org/10.1007/978-3-030-10618-8_12-1

Helm PA. Improving microplastics source apportionment: a role for microplastic morphology and taxonomy? Analytical Methods. 2017;9:1328–1331. https://doi:10.1039/c7ay90016c

Hidalgo-Ruz V, Gutow L, Thompson R, Thiel M. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environmental Science & Technology*. 2012;*46*(6):3060-3075. https://doi.org/10.1021/es2031505

Horton AA, Walton A, Spurgeon DJ, Lahive E, Svendsen C. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment*. 2017;586:127-141. https://doi.org/10.1016/j.scitotenv.2017.01.190

Hou B, Wang F, Liu T, Wang Z. Reproductive toxicity of polystyrene microplastics: In vivo experimental study on testicular toxicity in mice. *Journal of Hazardous Materials*. 2021;405: 124028. https://doi.org/10.1016/j.jhazmat.2020.124028

Hou J, Lei Z, Cui L, et al. Polystyrene microplastics lead to pyroptosis and apoptosis of ovarian granulosa cells via NLRP3/Caspase-1 signaling pathway in rats. *Ecotoxicology and Environmental Safety*. 2021;212:112012. https://doi.org/10.1016/j.ecoenv.2021.112012

Hu K, Yang Y, Zuo J, Tian W, Wang Y, Duan X, Wang S. Emerging microplastics in the environment: Properties, distributions, and impacts. *Chemosphere*. 2022;297:134118. https://doi.org/10.1016/j.chemosphere.2022.134118

Huang JN, Wen B, Zhu J-G, Zhang Y-S, Gao J-Z, Chen Z-Z. Exposure to microplastics impairs digestive performance, stimulates immune response and induces microbiota dysbiosis in the gut of juvenile guppy (Poecilia reticulata). *Science of the Total Environment*. 2020;733:138929. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.138929

Huang Y, Liu Q, Jia W, Yan C, Wang J. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environmental Pollution*. 2020;260:114096. https://doi.org/10.1016/j.envpol.2020.114096

Huang T, Zhang W, Lin T, et al. Maternal exposure to polystyrene nanoplastics during gestation and lactation induces hepatic and testicular toxicity in male mouse offspring. *Food and Chemical Toxicology*. 2022;160:112803. https://doi.org/10.1016/j.fct.2021.112803

Illinois General Assembly. *SB 1392 Public Act 101-0330*. (Reg. Sess. 2019). Retrieved June 15, 2022, from https://www.ilga.gov/legislation/publicacts/fulltext.asp?Name=101-0330

Illinois General Assembly. *SB 2727 Public Act 098-0638*. (Reg. Sess. 2014) Retrieved June 10, 2022, from https://www.ilga.gov/legislation/publicacts/fulltext.asp?Name=098-0638

Jambeck JR, Geyer R, Wilcox C, et al. Plastic waste inputs from land into the ocean. *Science*. 2015;347(6223):768-771. https://doi.org/10.1126/science.1260352

Jenkins T, Persaud BD, Cowger W, et al. Current State of Microplastic Pollution Research Data: Trends in Availability and Sources of Open Data [Original Research]. *Frontiers in Environmental Science*. 2022;10. https://doi.org/10.3389/fenvs.2022.912107

Jin H, Yan M, Pan C, et al. Chronic exposure to polystyrene microplastics induced male reproductive toxicity and decreased testosterone levels via the LH-mediated LHR/cAMP/PKA/StAR pathway. *Particle and Fibre Toxicology*. 2022;*19*(1):13. https://doi.org/10.1186/s12989-022-00453-2

Jin Y, Lu L, Tu W, Luo T, Fu Z. Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. *Science of the Total Environment*. 2019;649:308-317. https://doi.org/10.1016/j.scitotenv.2018.08.353

Kacprzak S, Tijing LD. Microplastics in indoor environment: Sources, mitigation and fate. *Journal of Environmental Chemical Engineering.* 2022;10(2):107359. https://doi.org/10.1016/j.jece.2022.107359

Karapanagioti HK, Rios Mendoza LM. Sorption of Pollutants on Microplastics. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-13. https://doi.org/10.1007/978-3-030-10618-8_9-1

Karasik R, Vegh T, Diana Z, et al. 20 Years of Government Responses to the Global Plastic Pollution Problem: The Plastics Policy Inventory. Duke University; 2020. Retrieved June 5, 2022, from https://nicholasinstitute.duke.edu/publications/20-years-government-responses-global-plastic-pollution-problem

Khan MT, Cheng YL, Hafeez S, Tsang YF, Yang J, Nawab A. Microplastics in Wastewater. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment* (pp.

1-33). 2020. Springer International Publishing. https://doi.org/10.1007/978-3-030-10618-8_39-1

Kim YN, Yoon JH, Kim KHJ. Microplastic contamination in soil environment – a review. *Soil Science Annual*. 2020;71(4):300-308. https://doi.org/10.37501/soilsa/131646 Ki

Kumar R, Verma A, Shome A, et al. Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions. *Sustainability*. 2021;13(17). https://doi.org/10.3390/su13179963

Kutralam-Muniasamy G, Shruti VC, Pérez-Guevara F, Roy PD. Microplastic diagnostics in humans: "The 3Ps" Progress, problems, and prospects. *Science of the Total Environment*. 2022;856(Pt 2):159164. https://doi.org/10.1016/j.scitotenv.2022.159164

La Merrill MA, Vandenberg LN, Smith MT, et al. Consensus on the key characteristics of endocrine-disrupting chemicals as a basis for hazard identification. *Nature Reviews: Endocrinology*. 2020;16(1):45-57. https://doi.org/10.1038/s41574-019-0273-8

Lamichhane G, Acharya A, Marahatha R, et al. Microplastics in environment: global concern, challenges, and controlling measures. *International Journal of Environmental Science and Technology*. 2022. https://doi.org/10.1007/s13762-022-04261-1

Lan T. Contaminant Release from Aged Microplastic. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-21. https://doi.org/10.1007/978-3-030-10618-8_11-1

Lau W, Murphy M. *Microplastics are a big—and growing—part of global pollution*. Pew. 2021. Retrieved August 3, 2022, from https://www.pewtrusts.org/en/research-and-analysis/articles/2021/03/30/microplastics-are-a-big-and-growing-part-of-global-pollution

LegiScan. *Bringing people to the process*. (2022). Retrieved July 14, 2022, from https://legiscan.com/

Legislative Assembly of Ontario. *Microbead elimination and monitoring act, 2015*. Retrieved June 10, 2022, from https://www.ola.org/en/legislative-business/bills/parliament-41/session-1/bill-75

Leslie HA, Brandsma SH, van Velzen MJM, Vethaak AD. Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. *Environment International*. 2017;101:133-142. https://doi.org/10.1016/j.envint.2017.01.018

Li J, Liu H, Paul Chen J. Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. *Water Research*. 2018;137:362-374. https://doi.org/10.1016/j.watres.2017.12.056

Li B, Ding Y, Cheng X, et al. Polyethylene microplastics affect the distribution of gut microbiota and inflammation development in mice. *Chemosphere*. 2020;244:125492. https://doi.org/https://doi.org/10.1016/j.chemosphere.2019.125492

Li J, Song Y, Cai Y. Focus topics on microplastics in soil: Analytical methods, occurrence, transport, and ecological risks. *Environmental Pollution.* 2020;257:113570. https://doi.org/10.1016/j.envpol.2019.113570

Li S, Wang Q, Yu H, et al. Polystyrene microplastics induce blood–testis barrier disruption regulated by the MAPK-Nrf2 signaling pathway in rats. *Environmental Science and Pollution Research*. 2021;28(35):47921-47931. https://doi.org/10.1007/s11356-021-13911-9

Li X, Zhang T, Lv W, et al. Intratracheal administration of polystyrene microplastics induces pulmonary fibrosis by activating oxidative stress and Wnt/β-catenin signaling pathway in mice. *Ecotoxicology and Environmental Safety*. 2022;232:113238.

Li Y, Shi T, Li X., et al. Inhaled tire-wear microplastic particles induced pulmonary fibrotic injury via epithelial cytoskeleton rearrangement. *Environment International*. 2022;164:107257.

Library of Congress (LOC). (2015). *S.1424 - 114th congress (2015-2016): Microbead-free waters.* Congress.gov. Retrieved June 9, 2022, from https://www.congress.gov/bill/114th-congress/senate-bill/1424/all-info

Lim D, Jeong J, Song KS, Sung JH, Oh SM, Choi J. Inhalation toxicity of polystyrene micro(nano)plastics using modified OECD TG 412. *Chemosphere*. 2021;262:128330.

Lind L, Araujo JA, Barchowsky A, et al. Key Characteristics of Cardiovascular Toxicants. *Environmental Health Perspectives*. 2021;129(9):095001.

Liu M, Lu S, Song Y, et al. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. *Environmental Pollution.* 2018;242:855-862. https://doi.org/10.1016/j.envpol.2018.07.051

Lu K, Lai KP, Stoeger T, et al. Detrimental effects of microplastic exposure on normal and asthmatic pulmonary physiology. *Journal of Hazardous Materials*. 2021;416:126069.

Lu L, Wan Z, Luo T, Fu Z, Jin Y. Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice. *Science of the Total Environment*. 2018;631-632: 449-458. https://doi.org/10.1016/j.scitotenv.2018.03.051

Luderer U, Eskenazi B, Hauser R, et al. Proposed Key Characteristics of Female Reproductive Toxicants as an Approach for Organizing and Evaluating Mechanistic Data in Hazard Assessment. *Environmental Health Perspectives.* 2019;127(7):75001. https://doi.org/10.1289/ehp4971

Macintosh SA, Neeman T, Dickson K. Plastic bag bans: Lessons from the Australian Capital Territory. *Resources, Conservation and Recycling*. 2020;*154*:104638. https://doi.org/10.1016/j.resconrec.2019.104638

Magalhães S, Alves L, Medronho B, Romano A, Rasteiro MDG. Microplastics in Ecosystems: From Current Trends to Bio-Based Removal Strategies. *Molecules (Basel, Switzerland)*. 2020;25(17):3954. https://doi.org/10.3390/molecules25173954

Malaysia Ministry of Environment and Water (MEW). *National Marine Litter Policy and Action Plan 2021 - 2030*. Retrieved June 16, 2022, from https://www.kasa.gov.my/resources/alam-sekitar/national-marine-litter-policy/36/

Mason SA, Garneau D, Sutton R, et al. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. *Environmental Pollution*. 2016;218:1045-1054. https://doi.org/10.1016/j.envpol.2016.08.056

Mathalon A, Hill P. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. *Marine Pollution Bulletin*. 2014;81(1):69-79. https://doi.org/10.1016/j.marpolbul.2014.02.018

Mendes, L. A. Microplastics Effects in the Terrestrial Environment. In T. Rocha-Santos M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-30. https://doi.org/10.1007/978-3-030-10618-8_46-1

Minnesota Legislature. (2022). *HF 3765*. Status in the House for the 92nd Legislature (2021 - 2022). Retrieved June 15, 2022, from https://www.revisor.mn.gov/bills/bill.php?b=house&f=hf3765&ssn=0&y=2022

National Academy of Sciences, Engineering, and Medicine (NASEM). *Application of systematic review methods in an overall strategy for evaluating low-dose toxicity from endocrine active chemicals*. The National Academies Press; 2017. https://www.nap.edu/catalog/24758/application-of-systematic-review-methods-in-an-overall-strategy-for-evaluating-low-dose-toxicity-from-endocrine-active-chemicals

National Academy of Sciences, Engineering, and Medicine (NASEM). *Progress toward transforming the Integrated Risk Information System (IRIS) program: A 2018 evaluation.* The National Academies Press; 2018. https://nap.nationalacademies.org/catalog/25086/progress-toward-transforming-the-integrated-risk-information-system-iris-program

National Academies of Sciences, Engineering, and Medicine (NASEM). *Guidance on PFAS Exposure, Testing, and Clinical Follow-Up*. The National Academies Press; 2022. https://doi.org/doi:10.17226/26156

National Congress of Argentina. *Law 27602 Plastic Microbeads in Cosmetic Products* (December 29, 2020). Retrieved June 13, 2022, from https://www.argentina.gob.ar/normativa/nacional/ley-27602-345720/texto

National Oceanic and Atmospheric Administration Marine Debris Program (NOAA MDP). *The Honolulu Strategy.* NOAA Marine Debris Program; 2011. Retrieved June 14, 2022, from https://marinedebris.noaa.gov/honolulu-strategy

National Oceanic and Atmospheric Administration Marine Debris Program (NOAA MDP). *Plastic marine debris.* NOAA Marine Debris Program; 2018. Retrieved November 12, 2022, from https://marinedebris.noaa.gov/sites/default/files/publications-files/2018_Plastics_Fact_Sheet.pdf

National Oceanic and Atmospheric Administration Marine Debris Program (NOAA MDP). *Mid-Atlantic Marine Debris Action Plan*. NOAA Marine Debris Program; 2021. Retrieved June 14, 2022, from https://marinedebris.noaa.gov/regional-action-plan/mid-atlantic-marine-debris-action-plan

National Oceanic and Atmospheric Administration, Marine Debris Program, Interagency Marine Debris Coordinating Committee (NOAA MDP). Draft Report on Microfiber Pollution: 2022 Report to Congress. NOAA Marine Debris Program; 2022. Retrieved September 15, 2022, from https://marinedebris.noaa.gov/interagency-marine-debris-coordinating-committee-reports/report-microfiber-pollution

National Research Council (NRC). *Toxicity Testing in the 21st Century: A Vision and a Strategy*. The National Academies Press; 2007. https://doi.org/doi:10.17226/11970

National Research Council (NRC). *Science and decisions: advancing risk assessment*. The National Academies Press; 2009. https://doi.org/10.17226/12209

National Research Council (NRC). *Review of EPA's integrated risk information system (IRIS) process* (Review of EPA's Integrated Risk Information System (IRIS) Process, Issue. The National Academies Press; 2014. https://doi.org/10.17226/18764

National Toxicology Program (NTP). *Handbook for conducting a literature-based health assessment using OHAT approach for systematic review and evidence integration*. 2019. Retrieved from https://ntp.niehs.nih.gov/ntp/ohat/pubs/handbookmarch2019_508.pdf

New Jersey State Legislature. *Bill S 864.* (Reg. Sess. 2020-2021). Retrieved June 15, 2022, from https://www.njleg.state.nj.us/bill-search/2020/S864

Norwegian Climate and Environment Ministry (CEM). *The Norwegian development program to combat marine litter and microplastics*. Ministry of Foreign Affairs, 2021. Retrieved June 14, 2022, from https://www.regjeringen.no/en/dokumenter/marine_litter/id2642037/

Organization for Economic Cooperation and Development (OECD). *Plastic leakage and greenhouse gas emissions are increasing. 2022.* Retrieved January 6, 2023, from https://www.oecd.org/environment/plastics/increased-plastic-leakage-and-greenhouse-gas-emissions.htm

Organization for Economic Cooperation and Development (OECD). *Policies to Reduce Microplastics Pollution in Water: Focus on Textiles and Tyres*, OECD Publishing, Paris. 2021. Retrieved June 17, 2022, from https://www.oecd-ilibrary.org/environment/policies-to-reduce-microplastics-pollution-in-water_7ec7e5ef-en.

Oslo and Paris Conventions Commission (OSPAR). *Marine Litter Regional Action Plan.* 2014. Retrieved June 14, 2022, from https://www.ospar.org/documents?v=34422

Parliament of Ireland. *Microbeads (prohibition) act 2019*. Bills and Acts. Retrieved June 13, 2022, from https://www.oireachtas.ie/en/bills/bill/2019/41/

Pelamatti T, Cardelli LR, Rios-Mendoza LM. The Role of Microplastics in Bioaccumulation of Pollutants. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-30. https://doi.org/10.1007/978-3-030-10618-8_18-1

Peller JR, McCool JP, Watters M. Microplastics in Soils and Sediment: Sources, Methodologies, and Interactions with Microorganisms. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-31. https://doi.org/10.1007/978-3-030-10618-8_38-1

Penn Bastola S, Hu W. Nudging Away from Plastic Bags with Charitable Donations. *Land Economics*. 2022;98(1):132–149. https://doi.org/10.3368/le.98.1.011820-0007R1

Prata JC, Castro JL, da Costa JP, Cerqueira M, Duarte AC, Rocha-Santos T. (2020). Airborne Microplastics. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-25. https://doi.org/10.1007/978-3-030-10618-8_37-2

Provencher JF, Covernton GA, Moore RC, Horn DA, Conkle JL, Lusher AL. Proceed with caution: The need to raise the publication bar for microplastics research. *Science of the Total Environment*. 2020;748:141426. https://doi.org/10.1016/j.scitotenv.2020.141426doi.org/

Ritchie H, Roser M. *Plastic pollution.* Our World in Data. Updated April 2022. Retrieved August 22, 2022, from https://ourworldindata.org/plastic-pollution

Rodriguez F. *Plastic.* Britannica. Updated September 21, 2022. Retrieved August 22, 2022, from https://www.britannica.com/science/domestication/Biological-and-genetic-changes

Rusyn I, Arzuaga X, Cattley RC, et al. Key Characteristics of Human Hepatotoxicants as a Basis for Identification and Characterization of the Causes of Liver Toxicity. *Hepatology*. 2021;74(6): 3486-3496. https://doi.org/10.1002/hep.31999

Sangkham S, Faikhaw O, Munkong N, et al. A review on microplastics and nanoplastics in the environment: Their occurrence, exposure routes, toxic studies, and potential effects on human health. *Marine pollution bulletin*. 2020;181:113832. https://doi.org/10.1016/j.marpolbul.2022.113832

Santos LHMM, Rodríguez-Mozaz S, Barceló D. Sorption of Pharmaceuticals on Microplastics. In T. Rocha-Santos, M. Costa, & C. Mouneyrac (Eds.), *Handbook of Microplastics in the Environment*. Springer International Publishing; 2020:1-36. https://doi.org/10.1007/978-3-030-10618-8_14-1

Saskia M, Smeets A, Malarciuc C, Tenhunen A, Fogh Mortenson L. *Microplastic pollution from textile consumption in Europe.* 2022. Retrieved September 12, 2022, from https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-products/etc-ce-report-1-2022-microplastic-pollution-from-textile-consumption-in-europe

Secretariat of the Pacific Regional Environment Program (SPREP). *Pacific Regional Action Plan: Marine Litter 2018-2025*. 2018. Retrieved June 17, 2022, from https://www.sprep.org/publications/pacific-regional-action-plan-marine-litter#:~:text=This%20Action%20Plan%20sets%20out,Pacific%20island%20Countries%20and%20Territories

Shahul HF, Bhatti MS, Anuar N, Anuar N, Mohan P, Periathamby A. Worldwide distribution and abundance of microplastic: How dire is the situation? *Waste Management & Research*. 2018.;36(10):873-897. https://doi.org/10.1177/0734242x18785730

Smith MT, Guyton KZ, Gibbons CF, et al. Key Characteristics of Carcinogens as a Basis for Organizing Data on Mechanisms of Carcinogenesis. *Environmental Health Perspectives*. 2016;124(6): 713-721. https://doi.org/10.1289/ehp.1509912

Southern California Coastal Water Research Project (SCCWRP). History of California Microplastics Legislation. 2022. Retrieved August 22, 2022 from https://www.sccwrp.org/about/research-areas/additional-research-areas/trash-pollution/microplastics-health-effects-webinar-series/history-california-microplastics-legislation/

State of California. *Green chemistry hazard traits for California's toxics information clearinghouse*. 2011. https://dtsc.ca.gov/dtsc-website-archive/green-chemistry/

Stapleton PA. Microplastic and nanoplastic transfer, accumulation, and toxicity in humans. *Current Opinion in Toxicology*. 2021;28:62-69. https://doi.org/10.1016/j.cotox.2021.10.001

Sutton R, Lin D, Sedlak M, Box C, et al. *Understanding Microplastic Levels, Pathways, and Transport in the San Francisco Bay Region*. SFEI Contribution No. 950. San Francisco Estuary Institute; 2019. Retrieved September 17, 2022, from https://www.sfei.org/documents/understanding-microplastics

Swedish Chemicals Agency (KEMI). *Plastic microbeads in Cosmetic Products*. Swedish rules on plastic microbeads in cosmetic products. Last updated 22 February 2022. Retrieved June 13, 2022, from https://www.kemi.se/en/rules-and-regulations/rules-applicable-in-sweden-only/certain-swedish-restrictions-and-bans/plastic-microbeads-in-cosmetic-products

Swedish Environmental Protection Agency (SEPA) (2019). *Microplastics in the Environment 2019*. Retrieved June 17, 2022, from https://www.naturvardsverket.se/globalassets/media/publikationer-pdf/6900/978-91-620-6957-5.pdf

ter Halle A, Ghiglione JF. Nanoplastics: A Complex, Polluting Terra Incognita. *Environmental Science & Technology*. 2021;55(21):14466-14469. https://doi.org/10.1021/acs.est.1c04142

Thompson, A. *Solving microplastic pollution means reducing, recycling—and fundamental rethinking.* Scientific American. Last updated November 18, 2018. Retrieved August 22, 2022, from https://www.scientificamerican.com/article/solving-microplastic-pollution-means-reducing-recycling-mdash-and-fundamental-rethinking1/

US Congress. *S.1982: Save Our Seas 2.0 Act.* (Reg. Sess. 2019-2020). Retrieved November 4, 2022, from https://www.congress.gov/bill/116th-congress/senate-bill/1982/text

US Environmental Protection Agency (EPA). *Guidelines for reproductive toxicity risk assessment*. 1996. Retrieved June 30, 2022, from https://www.epa.gov/sites/default/files/2014-11/documents/guidelines_repro_toxicity.pdf

US Environmental Protection Agency (EPA). Guidelines for carcinogen risk assessment. 2005. Retrieved June 30, 2022, from https://www3.epa.gov/airtoxics/cancer_guidelines_final_3-25-05.pdf

US Environmental Protection Agency (EPA). *Advancing sustainable material management: 2018 tables and figures.* Retrieved November 12, 2022, from https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf

US Environmental Protection Agency (EPA). Federal research on recycled tire crumb used on playing fields. Updated on July 5, 2022a. Retrieved December 28, 2022, from https://www.epa.gov/chemical-research/federal-research-recycled-tire-crumb-used-playing-fields

US Environmental Protection Agency (EPA). *IRIS glossary*. 2022b. Retrieved June 30, 2022, from https://www.epa.gov/iris/iris-glossary#tab1

US Environmental Protection Agency (EPA). *Plastics: Material-specific data.* Last updated on December 5, 2022c. Retrieved November 12, 2022, from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

United Kingdom Department of Environment, Food & Rural Affairs (DEFRA). Microbead ban announced to protect wildlife. 2016. Retrieved August 30, 2022, from https://www.gov.uk/government/news/microbead-ban-announced-to-protect-sealife

United Nations Environment Assembly (UNEA). *Resolution 1/6: Marine Plastic Debris and Microplastics*. United Nations Environment Program; 2014. Retrieved June 14, 2022, from https://www.ecolex.org/details/decision/marine-plastic-debris-and-microplastics-55d61f84-1850-42b7-ba62-7fc07d1829ec/

United Nations Environment Assembly (UNEA). *Resolution 2/11 Marine Plastic Litter and Microplastics*. United Nations Environment Program; 2016. Retrieved June 14, 2022, from https://wedocs.unep.org/handle/20.500.11822/11186

United Nations Environment Assembly (UNEA). *Resolution 3/7 Marine Litter and Microplastics.* United Nations Environment Program; 2018. Retrieved June 15, 2022, from https://wedocs.unep.org/

United Nations Environment Assembly (UNEA). *Resolution 11 on Protection of the Marine Environment from Land-Based Activities*. United Nations Environment Program; 2019a. Retrieved June 14, 2022, from https://wedocs.unep.org/bitstream/handle/20.500.11822/28475/English.pdf?sequence=3

United Nations Environment Assembly (UNEA). *Resolution 4/6 Marine Litter and Microplastics.* United National Environmental Program; 2019b. Retrieved June 14, 2022, from https://wedocs.unep.org/bitstream/handle/20.500.11822/28475/English.pdf?sequence=3

United Nations Environment Assembly (UNEA). *Resolution 4/7 Environmentally Sound Management of Waste*. United Nations Environment Program; 2019c. Retrieved June 14, 2022, from https://wedocs.unep.org/bitstream/handle/20.500.11822/28472/English.pdf?sequence=3

United Nations Environment Assembly (UNEA). *Resolution 5/11 End Plastic Pollution: Towards an international legally binding instrument.* United Nations Environment Program; 2022. Retrieved June 14, 2022, from https://wedocs.unep.org/bitstream/handle/20.500.11822/38522/k2200647_-_unep-ea-5-l-23-rev-1_-_advance.pdf?sequence=1

United Nations General Assembly (UNGA). *Action on Oceans and the Law of the Sea.* 2016. Retrieved June 14, 2022, from https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_71_257.pdf

Vermont General Assembly. H.446: An act relating to miscellaneous natural resources and development subjects. (Reg. Sess. 2021-2022). Retrieved November 10, 2022, from https://legislature.vermont.gov/bill/status/2022/H.446

Wen S, Zhao Y, Liu S, Chen Y, Yuan H, Xu H. Polystyrene microplastics exacerbated liver injury from cyclophosphamide in mice: Insight into gut microbiota. *Science of the Total Environment*. 2022;840:156668. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.156668

Wieland S, Balmes A, Bender J, et al. From properties to toxicity: Comparing microplastics to other airborne microparticles. *Journal of Hazardous Materials*. 2022;428:128151. http://doi.org/10.1016/j.jhazmat.2021.128151

Woodruff TJ, Sutton P. An evidence-based medicine methodology to bridge the gap between clinical and environmental health sciences. *Health Affairs (Millwood)*. 2011;30(5):931-937. https://doi.org/10.1377/hlthaff.2010.1219

Wu P, Huang J, Zheng Y, et al. Environmental occurrences, fate, and impacts of microplastics. *Ecotoxicology and Environmental Safety*. 2019;184:109612. https://doi.org/10.1016/j.ecoenv.2019.109612

Wu D, Feng Y, Wang R, et al. Pigment microparticles and microplastics found in human thrombi based on Raman spectral evidence. *Journal of Advanced Research*. 2022;806(part1):150263. https://doi.org/10.1016/j.jare.2022.09.004

Zhang C, Chen X, Wang J, Tan L. Toxic effects of microplastic on marine microalgae Skeletonema costatum: Interactions between microplastic and algae. *Environmental Pollution*. 2017;220, 1282-1288. https://doi.org/10.1016/j.envpol.2016.11.005

Zhang Q, Xu EG, Li J, Chen Q, Ma L, Zeng EY, Shi H. A Review of Microplastics in Table Salt, Drinking Water, and Air: Direct Human Exposure. *Environmental Science & Technology*. 2020;54(7), 3740-3751. https://doi.org/10.1021/acs.est.9b04535

Zhang Y, Kang S, Allen S, Allen D, Gao T, Sillanpää M. Atmospheric microplastics: A review on current status and perspectives. *Earth-Science Reviews.* 2020;203:103118. https://doi.org/10.1016/j.earscirev.2020.103118

Zhou Q, Zhang H, Fu C, Zhou Y, Dai Z, Li Y, Tu C, Luo Y. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. *Geoderma*. 2018;322. https://doi.org/10.1016/j.geoderma.2018.02.015

ABOUT CALSPEC

The California State Policy Evidence Consortium (CalSPEC) is an independent program administered through the University of California Center Sacramento (UCCS) and funded through the UC Office of the President. A group of faculty, graduate student researchers, and staff perform the analyses that inform CalSPEC reports. The CalSPEC **Faculty Steering Committee** with representatives from multiple University of California (UC) campuses recommends subject matter experts from their respective campuses, and reviews draft reports for clarity and responsiveness to legislative request. It also consults on improving CalSPEC approach to coordinating researchers across multiple UC campuses. The **Consortium Advisory Council** advises the CalSPEC team about organizational structure, subject matter expert recruitment, research processes, and policy communication. The CAC also reviews each draft report to ensure they are clear, objective, accurate, relevant, and reproducible. The CalSPEC staff coordinates the efforts of the Steering Committee and subject-specific research teams, and manages all external communications, including those with the California Legislature.

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