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MICROPLASTICS AND THEIR EFFECTS: ENVIRONMENTAL DISTRIBUTION, ANALYTICAL CHARACTERIZATION, AND ECOLOGICAL AND HUMAN HEALTH IMPLICATIONS

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Abstract
Microplastic pollution has become a widespread environmental concern due to the extensive use of plastic materials and their persistence in environment and possible interaction with biota. Microplastics are generally considered to be small pieces of plastic particles with a size less than 5 mm and they can originate either from fragmentation of larger plastic debris or from direct emissions from industrial, waste and consumer products. Microplastics have been detected in aquatic systems, terrestrial soils, atmospheric particles, indoor dust, food and the human body. This review critically covers the sources, environmental occurrences, analytical characterisation, pathways of exposure, and ecological and human health effects of microplastics. Attention was paid to recent advances in three innovative analytical techniques: FTIR, Raman spectroscopy and pyrolysis-GC/MS, while contamination and quality controls were considered as well. Experimental evidences suggest that some microplastics are able to produce oxidative stress, inflammation and physiological effects in some biological systems. However, the existing differences in particle properties, experimental conditions, methods and endpoints, prevent comparisons and direct application of results to human exposure. This review points out urgent methodological and toxicological issues, priorities in pollution monitoring, exposure assessment, pollution abatement and risk management.
Keywords: Microplastics; Environmental Pollution; Analytical Characterization; FTIR; Raman Spectroscopy; Pyrolysis–GC/MS; Oxidative Stress; Human Exposure; Ecotoxicology.

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1. Introduction

Plastics have become an essential part of our lives because they are able to be manufactured, manufactured and manufactured or manufactured utilising process to be lightweight, durable, versatile, inexpensive to produce and flexible enough to serve a large variety of applications. These applications include: packaging, agriculture, construction, textiles, transport, medicine, and consumer products. Plastic manufacturing, use, and disposal, have significantly contributed to plastics getting to be widespread and all-over environmental pollution.

According to the common definition, microplastics are plastic particles with size less than 5 mm. These include fibres, fragments, films, beads and irregularly shaped particles with different polymer types and surface properties. Primary microplastics are present in the environment due to the release of small particles during specific industrial or commercial use, while secondary microplastics are the result of degradation and fragmentation of larger plastic products. Polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyamide and polyurethane are the type of polymers mainly studied in environmental studies.

The relevance of microplastics for the environment is not only due to their prevalence, but also due to their persistence and ability to

move and interact with organisms and other pollutants. Pollution of water bodies occurs through discharges from the rivers and wastewater. Air pollution occurs from deposits from the air, from agriculture and from the degradation of plastic film. Land pollution is caused from synthetic textiles, carpets, upholstery and products used indoors[1],[2].



Figure 2. The above diagram shows sources of Microplastics.

Recent reviews have emphasized the necessity of refining analytical methods, characterizing environmental transport, and assessing human exposure potential. While the techniques used in these studies vary in their reported concentrations due to variations in sampling protocols, particle-size cutoffs, contamination controls, and polymer characterization methodology [1-3], such variations make interregion and intermatrices comparisons difficult.

A biological effect has been observed for a limited number of specific microplastics in experimental studies; however, information on potential impacts to human health is not yet complete[3]. Factors such as the size of the particle, the type of polymer, surface characteristics, additives, concentration and length of exposure all influence the degree of toxicity. Laboratory results cannot necessarily be extrapolated to greater population effects. This review will: (i) assess the main sources and eco-distribution of microplastics in the environment; (ii) consider analytical approaches for detection and characterization; (iii) collate data on ecological and possibly human-health impacts; (iv) consider where there are shortcomings in research, both in terms of knowledge gaps and experimental design; and (v) consider issues related to mitigation and research priorities[7].

3. Materials and Methods

3.1 Review design

This paper is written as a literature review based on published research relating to sources of, presence in the environment of, analysis of, exposure routes of, toxicity mechanisms for and impacts of microplastics. The literature review should be of an exacting standard for submission to a journal and should include a clear, reproducible approach for searching the literature and a description of how studies were selected in line with appropriate reporting guidelines (e.g., PRISMA 2020 [4]) where relevant.



Figure 2. The above diagram shows Environmental Distribution

3.2 Literature search strategy

For a systematic or structured review, the search of literature should be focused on such databases as Scopus, Web of Science, Pub Med, Google

Scholar. The search should be restricted to specific time period for which study was conducted, with basic earlier methodological papers.**Common search terms could be:**Microplastics" AND "environmental dispersion" -microplastics" AND "analytical characterization" -microplastics" AND "FTIR" OR "Raman spectroscopy" -microplastics" AND "Py-GC/MS" -microplastics" AND "human exposure" -microplastics" AND "oxidative stress" OR "ecotoxicity".Search dates, database names, full search strings, and any language/publication-year limits should be recorded prior to submission[8],[9].

3.3 Eligibility criteria

Studies will be included if they determine the occurrence, sampling, identification and quantification, environmental fate and exposure or biological effects of microplastics. Primary research articles, systematic reviews, critical reviews and methodological studies are all considered.The studies should be excluded from the review when they are not related to the review objectives, when they do not offer enough methodological details, or when they are related to plastic materials without a real link to microplastic contamination. The handling of conference abstracts, non peerreviewed reports, and nanoplastics only studies should be pre-specified[10].

3.4 Study selection and data extraction

Screen titles and abstracts to remove ineligible studies, then subsequently review full text articles of studies meeting inclusion criteria. Ideally at least two reviewers should independently screen and determine eligibility of studies, with discordance resolved by consensus or third reviewer.

Meta data must be extracted from each study including: year, location, sampling matrix, sampling strategy, particle size, polymer-identification method, abundance or mass concentration, exposure conditions, key findings, and limitations[11].

3.5 Evidence synthesis and quality assessment

The results should be summarized in thematic categories: environmental distribution, analytical techniques, human exposure, mechanisms of toxicity, and ecotoxicology. When comparing data, note the differences in sampling strategies, detection limits, particle-size designations, and units of reporting[12].A quantitative meta-analysis should be performed if data allow it, whereas a narrative synthesis should be used when the data do not compare easily or directly. Essential methodological information: the search dates, the number of records retrieved, the number of included studies, and the quality-assessment results should be filled in after the literature review has taken place, not fabricated. If the current paper is a narrative review, this should be indicated[13].

4. Analytical Characterization of Microplastics

4.1 Sampling and sample treatment

Representative sampling is necessary for accurate characterization due to high variability of microplastics in size, shape, material composition and spatial distribution. Environmental sample matrices such as surface water, wastewater, sediment, soil, atmospheric deposition, household dust, foods and biological matrices can contain microplastics, and sampling methods need to take into account each matrix and the anticipated particle size range. Contamination control is especially critical due to the presence of synthetic clothing, airborne fibres, plastic laboratory equipment and laboratory air containing extraneous particles[14]. Use of field blanks, procedural blanks and appropriate protective clothing, covered samples and documented quality-control procedures are thus vital elements of the analytical procedure.

Samples may be pre-treated for example by filtration, sieving, digestion of organic material and density separation. Some procedures employ solutions of sodium chloride, zinc chloride or sodium iodide to separate polymers according to their density and the density of the sample. However, recovery may depend on polymer type, particle size, weathering and the specific separation method used.

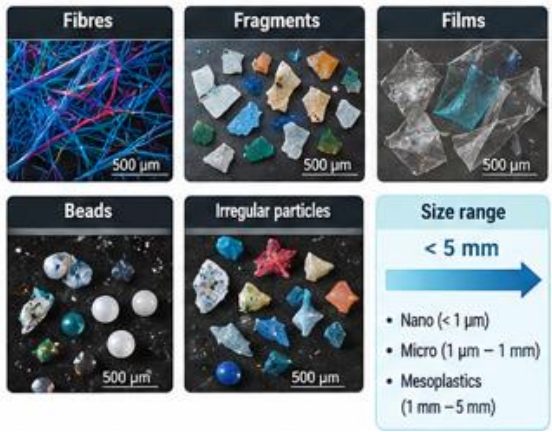


Figure 3. Morphological types and size classification of microplastics, showing fibres, fragments, films, beads, and irregular particles, with the size range classified as nano (<1 µm), micro (1 µm–1 mm), and mesoplastics (1–5 mm).

4.2 Microscopic Investigation

Optical microscopy and stereomicroscopy optical techniques may be employed in the initial visual analysis of suspected microplastic particles. They are capable of revealing details such as particle number, size, shape, colour, and visible surface properties. However, a visual analysis alone may not be sufficiently precise for identifying a plastic as other particles such as fibres, minerals, and natural particles can look similar.Therefore, when a definitive polymer identification is needed, the morphological evaluation should be complemented with a chemical identification method.

4.3 Fourier-transform infrared spectroscopy

FTIR Polymer Identification - Fourier transform infrared spectroscopy (FTIR) analyzes the type of polymer by detecting the characteristic IR absorption of its vibration modes. Micro-FTIR is an option to help identify and map polymer on individual particles on appropriate sample filters.

The detection rate is affected by particle size, the way the sample is prepared, the quality of the spectrum, polymer weathering and the availability of good reference libraries. The lower detection limit is also influenced by the measurement setup and instrument[15].

4.4 Raman spectroscopy

Raman spectroscopy to give molecular fingerprints in the inelastic scattering of light. Raman spectroscopy can have high spatial resolution and can be employed for locating small particles that can be challenging with a few FTIR configurations.However, pigment, organic matter, and weathered samples can produce fluorescence that swamps Raman signals. In addition, under some conditions laser irradiance can damage or heat sensitive particles. So proper acquisition parameters and spectral validation are required[16].

4.5 Pyrolysis-gas chromatography–mass spectrometry

Pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS) may identify polymer materials based on the characteristic pyrolysis products made during thermal decomposition. It can provide polymer-specific mass estimates and can be useful when trying to determine the amount of polymer in a more complex sample.Compared to microscopy particle counting techniques, the pyrolysis-GCMS analysis typically does not yield information on the count of the individual particles, their shape or size distribution. Py-GC/MS should be used as a complementary characterization approach to the more particle-based characterization[17].

4.6 Thermal analysis

Differential scanning calorimetry (DSC) detects thermal transitions (e.g. Melting and crystallization) and thermogravimetric analysis (TGA) measures changes in mass upon heating. These methods can give data about the thermal properties, stability and composition of the polymer but the specificity of the data depends on the type of sample and the method employed.

4.7 Analytical limitations and quality assurance

No one method offers every aspect of information: particle number, shape and shape distribution, identification of the polymer, particle size, and mass. However, a combination of microscopy with FTIR or Raman spectroscopy, and where feasible, py-GC/MS, can achieve a better characterization.Quality assurance should comprise as appropriate: blanks, recovery experiments, agreed validated spectral-identification criteria, reference materials where available and appropriate, and clear reporting of detection limits[18]. This is essential for comparability of research [1,2].

5. Results: Synthesis of Published Evidence

5.1 Environmental occurrence and distribution

Published research demonstrates that microplastics occur across aquatic, terrestrial, atmospheric, and indoor environments. Their distribution reflects multiple sources, including plastic waste degradation, textile shedding, road-related particles, wastewater discharge, agricultural activities, and industrial emissions. However, reported concentrations differ widely because environmental matrices, sampling volumes, particle-size cut-offs, analytical techniques, and reporting units are not consistent across studies. Consequently, simple comparisons between reported values may be misleading unless the methodological differences are considered.

5.2 Analytical characterization

The literature indicates that microscopy, FTIR, Raman spectroscopy, and thermal analytical methods provide complementary information. Microscopy supports particle counting and morphological assessment; FTIR and Raman spectroscopy provide molecular identification; and Py-GC/MS supports polymer-specific mass quantification. A recurring limitation is that studies based on different analytical platforms may measure different aspects of microplastic contamination. Particle counts cannot be directly equated with polymer mass, and differences in detection limits may influence the apparent abundance of particles in a sample[20].

5.3 Human exposure

Ingestion and inhalation are important potential exposure pathways, particularly through food, drinking water, indoor dust, and airborne particles. Reviews of indoor and outdoor air have highlighted the need for better harmonization of sampling, exposure estimation, and particle characterization [3]. Reports of microplastics in human biological samples have increased scientific interest, but interpretation remains challenging because of possible contamination, differences in detection methods, and uncertainty concerning the biological significance of detected particles.

5.4 Toxicological evidence

Experimental research has investigated oxidative stress, inflammation, cellular injury, gastrointestinal responses, respiratory effects, and reproductive or developmental outcomes. Some studies report adverse responses, whereas others show weaker or inconsistent effects depending on the experimental model and exposure conditions. The evidence should therefore be interpreted in relation to particle properties, dose, exposure route, duration, and environmental relevance. Findings from laboratory studies alone do not establish the magnitude of risk under typical human exposure conditions.

5.5 Ecological effects

Microplastics can be ingested by organisms across different trophic levels, including plankton, benthic invertebrates, molluscs, crustaceans, and fish. Potential outcomes investigated in the literature include changes in feeding behaviour, growth, energy allocation, reproduction, and physiological function.Nevertheless, ingestion does not necessarily indicate adverse effects, and the presence of particles in prey does not automatically demonstrate biomagnification through the food web. Long-term field observations are needed to determine the significance of these effects at population and ecosystem levels[21].

Interpretation of the results: These findings represent a qualitative synthesis of published literature, not new experimental measurements or a completed quantitative systematic review. Numerical summaries and formal statistical comparisons should be added only after the underlying studies have been systematically identified and their data extracted.

6. Discussion

6.1 Environmental persistence and transport

Microplastics are ubiquitous, showing that synthetic polymers are persistent and that there are numerous routes for plastic material to enter the environment. Fragmentation results in reduced particle size, but not in destruction of the polymer itself. Particle transport is dependent on particle density, shape, surface properties, weathering, aggregation, and interactions with biological material. The deposit of particles in sediments and soils raises concerns about the ability of those particles to be retained, remobilized and subsequently become bioavailable to habitat organisms living in sediment and soil. Transfer via the atmosphere also suggests a pathway of transfer between outdoor and indoor environments[24]. These processes suggest that microplastic pollution is an interconnected problem affecting our environment, not only the oceans.

6.2 Importance of analytical standardization

One of the major hurdles in microplastic research is analytical comparability. Similarly, various studies have been conducted with different types of filters, digestion protocols, size cut-off sizes, spectral libraries, and identification criteria, which can result in very different estimates of samples from a similar environment. For ID confirmation, FTIR and Raman are especially useful whereas Py-GC/MS offers additional information on the polymer mass. The task-dependent decisions of these techniques should be driven by the research question not by the notion that one is better than the other. Subsequent research will report sampling design, recovery rates, blank corrections, particle-size limits, detection limits, polymer-identification specifications, and units of measurement in enough detail that results can be evaluated and replicated[26].

6.3 Possible mechanisms of toxicity

Experimental studies have also looked at oxidative stress, inflammation, the effects of physical contact with biological barriers, and chemicals associated with plastics. Characteristics of particles, including size, shape, surface chemistry, weathering and polymer additives, could impact the effects on living organisms. It will be important to distinguish, at least at some level, between effects caused by the physical particle; effects related to chemicals released from plastic; and effects relating to other contaminants attached to the particle. These mechanisms may converge, but they cannot be assumed to be interchangeable[27]. Concentrations and durations of exposure used in the studies should also be compared to realistic environmental conditions. In cases where the experiments involve high concentrations or reductionist

laboratory systems, the data can suggest biologic plausibility but not quantify the extent of risk.

6.4 Human-health implications

Microplastics in food, air and some humans' biological samples make further investigations into potential exposure routes worthwhile. Nevertheless, there are differences between exposure and causation of disease. The absence of evidence of particles does not prove a human disease was not caused by these.They will need validated analytical methods, consistent exposure measures, well-designed epidemiological studies, and assessment of confounding factors. Research should separate particle number, polymer mass, and particle-size distribution, as each measure provides unique information[28].

6.5 Ecological implications and food-web transfer

Marine organisms from a variety of habitats have been known to ingest microplastics and ecological impacts will vary depending on particle composition, density of exposure, feeding strategies and the capacity of the organism to expel particles. Impacts seen at the individual level should not be automatically assumed at populations. Similarly, the trophic transfer of particles should be distinguished from biomagnification; there is no requirement for particles to increasingly accumulate higher up in the trophic levels. Additional work should be done to quantify losses and retention of particles, and determine whether there are significant impacts on survival, reproduction, community structure or ecosystem processes[29].

6.6 Research priorities and environmental management

The requirements found from the literature are: standardized sampling protocols, better detection of smaller particles, conclusive contamination control, more realistic exposure experiments, and long-term monitoring. There is a need for more comprehensive studies to link environmental concentrations to biological impact and exposure. Mitigation efforts should include: preventing plastic release as much as possible via source reduction, better waste management and industrial loss control, addressing textile-related issues and ensuring wastewater is treated effectively. The breakdown and transfer of captured particles must be taken into consideration. Such policy and practice interventions are likely to be best informed by an integrated approach drawing on analytical chemistry, environmental science, toxicology, epidemiology and research on waste-management [18].

7. Conclusion

Some, Sources, Transport pathways, compartments and effects microplastic pollution is a complex environmental problem with multiple sources, transport pathways and compartments and potential effects. The published literature over the last 10 years reveals the widespread presence in aquatic and terrestrial systems as well as in atmospheric aerosols, indoor dust and matrices related to exposure. Techniques for characterisation using microscopy, FTIR, Raman spectroscopy or Py-GC/MS have been developed but inconsistencies in detection limits, sample preparation and reporting further complicate inter-study comparisons. Experimental data have shown that some microplastics elicit oxidative stress, inflammatory response, and physiological alterations in some select biological models. However, the impact and potential human-health risk from real-world exposure remains uncertain. Sufficient data for firm conclusions require more reliable analytical methodology, better exposure assessment, better control of contamination, and longer-term studies. Further studies should be based on a combination of environmental sampling, chemical analysis, toxicology research and epidemiology. Meanwhile, a wise

implementation of preventive measures such as minimizing of plastic use, recycling, enhancing collection and treatment of waste, avoiding release from industrial processes and protective measures through environmental monitoring can prevent further pollution. Overall, a prudent, evidence-based application of information will demonstrate the role of microplastics in pollution impact and reduce the damage.

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