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REVIEW ARTICLE

# Nanoplastics in the environment: sources, impacts, and challenges

## Nanoplásticos en el medio ambiente: fuentes, impactos y desafíos

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**Abstract** Nanoplastics, defined as plastic particles with dimensions less than 1 µm, represent a growing environmental concern due to their ubiquity and potential adverse effects on ecosystems and human health. This review article analyses the primary sources of nanoplastics, their distribution in different environmental compartments (water, soil, and air), and their mechanisms of toxicity in aquatic and terrestrial organisms. Current methodologies for their detection and characterization are also examined, including spectroscopic, chromatographic, and electron microscopy techniques, highlighting their advantages and limitations. Despite progress in understanding the presence and impact of nanoplastics, significant research gaps remain, particularly about their bioaccumulation, interactions with emerging contaminants, and long-term effects on human health. Potential strategies to mitigate their impact are also identified, such as improved plastic waste management, developing biodegradable materials, and implementing stricter regulatory policies. Developing new detection methods and adopting sustainable strategies are essential to reduce the burden of nanoplastics in ecosystems and minimize their risks to public health.

**Keywords** nanoplastics, environmental pollution, ecotoxicology, analytical detection, bioaccumulation, health impact.

**Resumen** Los nanoplásticos, definidos como partículas de plástico con dimensiones inferiores a 1 µm, representan una creciente preocupación ambiental debido a su ubicuidad y potenciales efectos adversos en los ecosistemas y la salud humana. Este artículo de revisión analiza las principales fuentes de nanoplásticos, su distribución en distintos compartimentos ambientales (agua, suelo y aire) y sus mecanismos de toxicidad en organismos acuáticos y terrestres. Se examinan además las metodologías actuales para su detección y caracterización, incluyendo técnicas espectroscópicas, cromatográficas y de microscopía electrónica, destacando sus ventajas y limitaciones. A pesar del avance en la comprensión de la presencia e impacto de los nanoplásticos, persisten vacíos de investigación significativos, particularmente en relación con su bioacumulación, interacciones con contaminantes emergentes y efectos a largo plazo en la salud humana. Asimismo, se identifican estrategias potenciales para mitigar su impacto, como la mejora en la gestión de residuos plásticos, el desarrollo de materiales biodegradables y la implementación de políticas regulatorias más estrictas. El desarrollo de nuevos métodos de detección y la adopción de estrategias sostenibles son esenciales para reducir la carga de nanoplásticos en los ecosistemas y minimizar sus riesgos para la salud pública.

**Palabras clave** nanoplásticos, contaminación ambiental, ecotoxicología, detección analítica, bioacumulación, impacto en la salud.

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PUBLIS EDITORIAL

## Introduction

Plastic pollution is an environmental and public health challenge that has escalated to critical levels. In particular, nanoplastics, defined as plastic particles of nanometric size (<100 nm), pose a unique threat related to their ability to biological systems interaction at the cellular and molecular levels. These interactions can trigger complex toxic effects in various organisms, including physiological alterations and cellular damage (Gigault et al., 2018).

Despite the growing interest in microplastic research (Castañeta et al., 2020), studies on nanoplastics are still limited, making it difficult to understand their distribution, persistence, and toxicity. Two main sources of nanoplastics have been identified: primary nanoplastics, manufactured for specific applications such as cosmetics or industrial coatings, and secondary nanoplastics, formed by the fragmentation of larger plastics through mechanical, chemical, or photo-oxidative processes (Amobonye et al., 2021).

Given their mobility and ubiquity, nanoplastics have been detected in various environmental compartments, such as water, air, soil, and human foods (Allen et al., 2022). This raises serious concerns about their ecological and human health impacts, including risks of bioaccumulation, cellular inflammation, and potential genetic alterations.

This article aims to analyze nanoplastics in terms of their sources, environmental distribution, toxic effects, detection methods, and research gaps to identify strategies that reduce their impact on ecosystems and public health.

## Sources and generation of nanoplastics

Nanoplastics are classified according to their origin as primary and secondary and are generated and released into the environment through multiple pathways, increasing their presence in various settings. Primary nanoplastics are intentionally produced for industrial applications, cosmetics, and pharmaceuticals. In contrast, secondary nanoplastics are generated from the degradation of larger plastics through mechanical, chemical, and photo-oxidative processes (Ziani et al., 2023). The release of nanoplastics into the environment occurs through various pathways, including the washing of synthetic textiles, the fragmentation of plastic containers, and the dispersion of paints and coatings.

## Primary nanoplastics

The most notable uses of primary nanoplastics include industrial, pharmaceutical, cosmetic, and personal care applications. They manufacture advanced products such as water-resistant coatings, reinforced materials, and electronics in the industry. In cosmetics and personal care products, they are used as microbeads or plastic nanoparticles added to exfoliants, toothpaste, and sunscreens; these particles act as abrasives, stabilizers, or controlled release agents for active ingredients (Karbalaei et al., 2018).

They are also employed in drug encapsulation to improve bioavailability or target the release to specific tissues. Although these materials are designed for functional applications, their release mainly occurs during the manufacturing process, use, or improper disposal of products, facilitating their entry into the environment.

## Secondary nanoplastics

Secondary nanoplastics are generated from the fragmentation of larger plastics due to various degradative processes. These include mechanical processes such as physical wear caused by abrasion on roads, the crushing of plastic waste, and maritime activities like fishing and transportation. Chemical degradation occurs when polymers react with chemical agents present in the environment, such as oxidants and free radicals, causing their breakdown into smaller particles. Additionally, photooxidation, catalyzed by the sun's ultraviolet (UV) light, decomposes polymer chains into nanoparticles, a phenomenon particularly common in plastics exposed in aquatic and terrestrial environments. The gradual fragmentation of macro and microplastics creates nanometric particles, increasing transport risk to higher trophic levels and their accumulation in biological tissues (Rashed et al., 2023).

## Distribution and transformation in the environment

Due to their small size, nanoplastics are highly mobile and can be widely distributed across various environmental compartments, such as water, soil, and air (Brewer et al., 2021). Additionally, their persistence is influenced by factors such as chemical composition, environmental conditions, and interactions with other pollutants.

The persistence of nanoplastics in the environment raises fundamental questions about their degradation rates and the products resulting from their transformation. These factors are key to understanding their ecological impact and life cycle, as they determine how long they remain in ecosystems and how they interact with living organisms.

One of the main challenges is their slow degradation. Nanoplastics are highly resistant to chemical, biological, and photo-oxidative degradation processes, which prolong their presence in the environment and increase their potential for bioaccumulation. Their stability allows them to persist in different environments for long periods, facilitating their dispersion and possible incorporation into trophic chains.

Moreover, under environmental conditions, nanoplastics can undergo surface transformations, such as oxidation or the formation of biofilms. These modifications can alter their behavior and toxicity, affecting their interaction with microorganisms and other aquatic organisms.

A study analyzing the degradation rates of nanoplastics in simulated seawater found that after one year of exposure, only 5% of the particles exhibited significant chemical alterations. This finding highlights their persistence and the risk of accumulation in marine ecosystems, emphasizing the need to understand their long-term impact better (Tosetto et al., 2022).

## Ecological impact

Studies indicate that nanoplastics can bioaccumulate in aquatic organisms, affecting their physiology and behavior. They can also alter soil microbial communities, compromising soil fertility and ecosystem health. Nanoplastics can cross biological membranes and generate inflammatory responses and cellular damage in model organisms (Jayavel et al., 2024). Nanoplastics also significantly impact terrestrial ecosystems, particularly in the soil, where they interact with microorganisms, affecting soil fertility and biogeochemical cycles.

## Bioaccumulation in aquatic organisms

Nanoplastics can be accidentally ingested by various aquatic organisms, from zooplankton to fish, by confusing them with food particles. When absorbed and retained in aquatic organisms, bioaccumulation occurs. This ingestion can lead to intestinal blockages, reduced nutrient absorption, and changes in feeding behavior. As they accumulate in the food chain, these particles can affect higher predators, including birds and marine mammals (Trevisan et al., 2022).

A study on oysters *Crassostrea gigas* exposed to polystyrene nanoplastics showed a significant reduction in their reproductive capacity. The results indicated that the particles accumulated in the gills and digestive system, affecting nutrient filtration and causing oxidative stress in the organisms (Cole et al., 2015).

## Alteration of soil microbial communities

It has been shown that nanoplastics in agricultural soils can negatively affect plant growth by generating oxidative stress and metabolic alterations. The chemical compounds released by these materials cause cellular and genetic damage, and their presence modifies the soil conditions, impacting its fertility. Combining different microplastics can enhance their toxicity (Russo et al., 2023). A study on soils treated with polyethylene nanoplastics showed alterations in the composition and activity of microbial communities, reducing the soil's ability to process organic matter (Bodor et al., 2024).

## Toxic impact on human health

Chronic exposure to nanoplastics generates uncertainty regarding their long-term effects on human health, although the lack of longitudinal data and standardized methodologies limits their study. Key areas of uncertainty include bioaccumulation, meaning the ability of nanoplastics to accumulate in human tissues with potential effects on specific organs; transgenerational effects, suggesting a potential impact on the health of future generations due to maternal exposure; and combined effects arising from the interaction of nanoplastics with other pollutants or environmental factors. An experiment conducted on mice chronically exposed to nanoplastics showed metabolic alterations, liver dysfunction, and changes in the gut microbiome, highlighting the need for long-term studies in humans (Lu et al., 2020).

The accumulation of nanoplastics in organs has been studied in animal models, where their presence has been observed in the liver, kidneys, brain, and lungs. This accumulation has been linked to oxidative stress, inflammation, and liver toxicity (Haldar et al., 2023). Exposure to nanoplastics could lead to infertility, possibly related to potential epigenetic changes.

Routes of exposure to nanoplastics include inhalation and ingestion. Inhaled particles may come from sources such as tire wear, fragmentation of synthetic textiles, and industrial activity. Once in the air, they can be inhaled and deposited in the lungs, possibly entering the bloodstream, depending on their size. A study in urban environments identified an association between exposure to plastic particles in the air and an increased risk of chronic respiratory diseases, such as asthma and pulmonary fibrosis (Li et al., 2022).

Ingestion is another important route of exposure, with food and water being the primary sources through which nanoplastics enter the digestive system. These particles have been identified in fish, shellfish, table salt, and bottled water products. Research has detected concentrations of up to 10,000 particles per liter in bottled water, indicating a high exposure through this route (Mason et al., 2018). Similarly, in shellfish such as mussels and clams, nanoplastic accumulation has been demonstrated, and nanoplastics are subsequently consumed by humans (Cauwenberghe & Janssen, 2014).

## Identified adverse effects

Nanoplastics can induce oxidative stress by generating reactive oxygen species (ROS), which damage cellular components such as lipids, proteins, and DNA. This mechanism has been linked to the development of chronic diseases, including cancer, diabetes, and neurodegenerative conditions (Kadac-Czapska et al., 2024). A study on human cell lines demonstrated that polystyrene nanoplastics can induce oxidative stress and mitochondrial damage in intestinal epithelial cells (Schirinzi et al., 2017).

In addition to oxidative stress, exposure to nanoplastics can trigger inflammatory responses in various body tissues. Their accumulation in organs such as the intestine, lungs, and liver can activate the immune system, promoting chronic inflammation. In an in vitro model, it was observed that polyethylene nanoplastics induced a strong inflammatory response in human immune cells, similar to the response triggered by bacterial pathogens (Stock et al., 2019).

Another risk associated with nanoplastics is that they can cross biological barriers, such as intestinal and blood-brain barriers, allowing them to accumulate in specific organs and cause toxicity. A study on mice exposed to polystyrene nanoplastics revealed their presence in the liver, kidneys, and brain, resulting in liver inflammation, renal damage, and neurological alterations (Lu et al., 2024).

## Challenges in risk assessment

Research on the effects of nanoplastics on human health faces several limitations. There is a lack of data from human studies, as most research has been conducted on animal models or in vitro systems. This lack of direct evidence makes it difficult to extrapolate the results to the human population. In many studies, the doses and concentrations of nanoplastics used were significantly higher than those of daily exposure, which may generate uncertainty about the risks (Yee et al., 2021).

Another limitation is the lack of analytical standards for detecting and quantifying nanoplastics in biological and environmental matrices. Currently, there is no consensus on the most appropriate methods for their analysis, which complicates comparing results between studies and hinders accurate risk assessment of these pollutants.

## Inflammatory responses and cellular damage

Due to their small size, nanoplastics can traverse various biological membranes, including the intestinal, blood-brain, and cellular barriers. This ability facilitates their distribution within the body and can lead to inflammatory responses and damage to organs and tissues. A real example of this phenomenon was observed in an experiment with zebrafish (Danio rerio), where polystyrene nanoplastics induced intestinal inflammation and liver damage. Additionally, particles were found in the fish's brain, suggesting that the nanoplastics could cross the blood-brain barrier (Mattsson et al., 2017).

The effects of nanoplastics on model organisms include generating ROS, which causes oxidative stress and cellular damage. Their accumulation in sensitive tissues can trigger chronic inflammation, contributing to various pathologies. Another observed toxicity mechanism is apoptosis, or programmed cell death, induced by the direct interaction of nanoplastics with intracellular structures (Geremia et al., 2023).

The ecological and toxic effects of nanoplastics not only impact biodiversity and ecosystem stability but pose potential risks to human health. Bioaccumulation in aquatic organisms, the alteration of microbial communities in soil, and inflammatory responses in model organisms emphasize the need for urgent action (Habumugisha et al., 2024). To mitigate these impacts, it is essential to reduce the release of nanoplastics into the environment through better waste management practices, promote the development of alternative biodegradable materials, and establish stricter regulations on using primary plastics in commercial products. Implementing these actions immediately is crucial to prevent irreversible ecological damage and protect public health in the future (Kumar et al., 2021).

## Specific toxicity mechanisms of nanoplastics

Several factors complicate the assessment of their toxicity. One of them is the chemical and physical heterogeneity of nanoplastics, as they vary in composition (e.g., polyethylene, polypropylene), size, shape, and surface properties, which influences how they interact with biological systems (Xuan et al., 2023). Nanoplastics can adsorb chemical or biological contaminants, acting as carriers for toxic substances and indirectly increasing their harmful potential.

A study conducted on a human cell model demonstrated that polystyrene nanoplastics altered the permeability of the cell membrane, facilitating the absorption of heavy metals such as cadmium. The toxicity of nanoplastics depends on their intrinsic properties and the contaminants they carry, which amplifies their negative impact on exposed organisms (Masson et al., 2023).

## Analytical techniques for nanoplastic detection

The detection, quantification, and characterization of nanoplastics in food, pharmaceuticals, and other complex matrices allow their health and environmental impact evaluation. These particles present analytical challenges due to their nanometric size, chemical and physical heterogeneity, and interactions with the matrices in which they are present. The most commonly used techniques are transmission electron microscopy (TEM), Raman spectroscopy and Fourier Transform Infrared Spectroscopy (FTIR), and chromatography coupled with mass spectrometry (Berkel & Özbek, 2024).

### Transmission electron microscopy

TEM is a technique for directly observing nanoplastics, allowing high-resolution images to be obtained to determine their size, morphology, and surface characteristics. Its principle uses an electron beam that passes through an ultrathin sample, generating a detailed image of the nanometric particles (Mariano et al., 2021). Its advantages include high resolution and the ability to reveal morphological details, although its use involves limitations such as the need for ultrathin samples, high costs, and technically complex operation.

### Raman spectroscopy

Spectroscopic techniques are essential for identifying the chemical composition of nanoplastics by analyzing their molecular vibrations. Based on the Raman effect, Raman spectroscopy measures the inelastic scattering of laser light as it interacts with the sample, providing information on the molecular vibrations of polymers (Nava et al., 2021). A study conducted by Mason et al. (2018) used this technique to analyze the content of nanoplastics in bottled water, identifying polystyrene and polyethylene particles with sizes smaller than 1 µm.

### Fourier Transform Infrared spectroscopy

FTIR spectroscopy is a technique that measures the absorption of infrared light by the molecules of a sample, generating a characteristic spectrum that allows the identification of the present polymers (Kassem et al., 2023). Van Cauwenberghe and Janssen (2014) used FTIR to analyze mussels intended for human consumption, confirming the presence of polypropylene nanoplastics with an average concentration of 2.2 particles per gram of tissue. Among its advantages, this technique is non-destructive and proper for qualitative and quantitative analysis, although its resolution may be limited for extremely small particles, especially those smaller than 1 µm.

### Chromatography coupled with mass spectrometry

Gas chromatography coupled with mass spectrometry (GC-MS) or liquid chromatography coupled with mass spectrometry (LC-MS) is a technique used to analyze the thermal degradation products of nanoplastics, providing detailed information about their chemical composition. Its principle is based on the thermal or chemical decomposition of nanoplastics (Niu et al., 2024), which releases monomers that are then separated by chromatography and analyzed by mass spectrometry for identification.

Among its advantages, this technique offers high sensitivity and specificity for identifying polymers and additives. However, it has limitations, such as the need for sample pretreatment and the inability to detect intact particles in some cases.

### Comparison of the techniques

The analysis of nanoplastics in food and pharmaceuticals requires advanced analytical techniques that allow for their identification, characterization, and quantification at trace levels. Table 1 compares three key methods in this field: TEM, Raman/FTIR spectroscopy, and gas or liquid chromatography coupled with mass spectrometry (GC-MS/LC-MS). Each of these techniques provides complementary information for detecting nanoplastics in complex matrices.

TEM is one of the most commonly used tools for morphological characterization and size determination of nanoplastics in food and pharmaceuticals. Its nanometric resolution allows for the visualization of structures with high precision, which is crucial for confirming the presence of plastic particles in consumer products. However, its main limitation lies in the need to prepare ultrathin samples, which can alter the distribution of particles or even induce artifacts during observation.

Raman spectroscopy and FTIR spectroscopy are widely used for the chemical identification of nanoplastics. Their

**Table 1.** Comparison of analytical techniques for the detection and characterization of nanoplastics in food and pharmaceuticals

| Technique | Main uses | Advantages | Limitations |
|---|---|---|---|
| TEM | Morphology and size | Nanometric resolution | Ultrathin samples required |
| Raman/FTIR | Chemical identification | Non-destructive, fast | Limited resolution (<1 μm) |
| GC-MS/LC-MS | Chemical composition through decomposition | High sensitivity | Indirect analysis |

non-destructive nature and fast analysis make them particularly useful for detecting micro and nanoplastics in processed foods and pharmaceutical formulations. However, they present limited spatial resolution, especially for particles at the nanometric scale (<1 μm), which complicates the identification of smaller fragments and can cause interference with other components of the food or pharmaceutical matrix.

On the other hand, Gas or Liquid Chromatography coupled with Mass Spectrometry (GC-MS/LC-MS) is a reference technique for identifying polymers through the thermal or chemical decomposition of nanoplastics into their monomers or characteristic fragments. Its high sensitivity allows for detecting ultra-low concentrations in food and pharmaceuticals, which is crucial for assessing human exposure to these particles. However, one of its main limitations is that the analysis is indirect, as it requires the degradation of nanoplastics into their essential components, which may hinder the precise identification of the original polymer structure.

Detecting nanoplastics in food and pharmaceuticals requires combining analytical techniques to address their physical and chemical complexity. TEM microscopy provides morphological information, while spectroscopic techniques (Raman and FTIR) identify the chemical composition. Meanwhile, chromatography coupled with mass spectrometry complements these techniques by analyzing thermal decomposition products.

The integration of these techniques allows for robust characterization, facilitating the assessment of risks associated with neoplastic contamination and promoting strategies to reduce their presence in consumer products. Table 2 shows the type and concentration of nanoplastics detected in some foods.

## Conclusions

Despite the advancements in research, uncertainties about the toxicity mechanisms, degradation rates, and long-term effects of nanoplastics on human health underscore the urgent need for more studies. These emerging pollutants, with significant implications for ecosystems and health, require an interdisciplinary approach that combines scientific research, environmental regulation, and public education. Developing standardized methodologies and assessing chronic impacts are essential for fully understanding the associated risks and designing effective mitigation strategies, including reducing plastic production, promoting alternative materials, and strengthening waste management. Nanoplastics represent an emerging concern due to their ubiquity in the environment and their potential impact on human health and ecosystems. However, despite scientific progress, several areas of uncertainty persist, hindering a comprehensive understanding of the associated risks. These uncertainties are related to toxicity mechanisms, environmental degradation rates, and long-term effects on human health. Below, each of these points is analyzed and explored in greater detail.

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**Table 2.** Concentration of nanoplastics detected in some foods

| Reference | Plastic material | Contaminated foods | Nanoplastic concentration |
|---|---|---|---|
| Karami et al. (2017) | PE, PP, PS | Fish, seafood | 0.3-0.9 particles/g |
| Liebezeit & Liebezeit (2013) | PE, PP | Honey | 0.166 ± 0.138 fibers/g |
| Liebezeit & Liebezeit (2014) | PE, PP | Sugar, table salt | 0.44 ± 0.33 particles/kg (salt); 0.11 ± 0.08 particles/kg (sugar) |
| Kosuth et al. (2018) | PET, PP | Bottled water | 10.4 particles/L |
| Mason et al. (2018) | PET, PP | Tap water | 5.45 particles/L |
| Liebezeit & Liebezeit (2015) | PE, PP | Beer | 0-14.3 particles/L |
| Catarino et al. (2018) | PE, PP | Mussels | 0.36 ± 0.07 particles/g |
| Van Cauwenberghe & Janssen (2014) | PE, PP | Mussels, oysters | 0.36 ± 0.07 particles/g (mussels); 0.47 ± 0.16 particles/g (oysters) |
| Karami et al. (2018) | PE, PP | Fish | 1-7 particles/fish |
| Schwabl et al. (2019) | PE, PP | Human feces (indicative of food intake) | 20 particles/10 g of feces |
| Peixoto et al. (2019) | PE, PP | Table salt | 0-1674 particles/kg |
| Iñiguez et al. (2017) | PE, PP | Table salt | 50-280 particles/kg |
| Karbalaei et al. (2019) | PE, PP | Fish, seafood | 0.2-0.8 particles/g |
| Gündoğdu (2018) | PE, PP | Table salt | 16-84 particles/kg |
| Yang et al. (2015) | PE, PP | Table salt | 550-681 particles/kg |
| Liebezeit & Dubaish (2012) | PE, PP | Seafood | 0.2-0.5 particles/g |
| Rochman et al. (2015) | PE, PP | Fish, seafood | 2.1 particles/fish |
| Van Cauwenberghe et al. (2015) | PE, PP | Seafood | 0.36 ± 0.07 particles/g |
| De Witte et al. (2014) | PE, PP, PS | Mussels | 0.26 ± 0.20 particles/g |

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### Conflicts of interest

The author declares that she has no conflict of interest.

### Author contributions

**Daliannis Rodríguez:** Conceptualization, research, methodology, visualization, writing the original draft, writing, review and editing.

### Data availability statement

Not applicable.

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