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MICRO- AND NANOPLASTICS: IMPACT ON THE ECOSYSTEM AND WAYS TO REDUCE THEIR FORMATION (A Review)

Sarymsakov A.A., Yuldoshov Sh.A.

Institute of Polymer Chemistry and Physics Uzbekistan Academy of Sciences, 100128, Tashkent, Uzbekistan

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Corresponding author: Yuldoshov Sh.A.
sherzodbek_y@mail.ru

ABSTRACT

This review article provides a comprehensive analysis of current literature sources addressing the formation processes of microplastics and nanoplastics in the environment, as well as assessing their negative impact on ecosystems and human health. Special attention is given to the sources of these particles, the mechanisms of their spread, and their bioaccumulation within food chains. The article examines existing technologies and approaches for the capture, identification, sorting, and processing of micro- and nanoplastics, including mechanical, physicochemical, and biological methods. Promising directions for reducing their formation are discussed, such as the implementation of biodegradable materials, tightening regulatory requirements for the production and disposal of plastics, and the development of environmental monitoring systems. This material may be useful for specialists in ecology, toxicology, materials science, and environmental protection.

Introduction

Formation, Classification, and Environmental Significance of Microplastics and Nanoplastics

Microplastics are microparticles ranging in size from several micrometers to nanometers, which are formed during the use of polymer products and the decomposition of polymer-plastic waste under natural conditions [1]. Today, there is virtually no industry or sphere of human activity that does not utilize polymers [2]. The main sources of microplastics include: cosmetic and cleansing products, synthetic fabrics (from which microplastics are released during washing), plastic-coated fertilizers, plastic films used in agriculture, rubber granules found in artificial turf, recycled polymer-plastic waste, and large volumes of polymer-plastic waste sent to landfills [3].

Microplastics are conventionally divided into two groups. The first group consists of microplastics formed from natural polymers and their heterochain polymer derivatives [4]. These types of microplastics tend to degrade in natural environments over a relatively short period [5]. The second group includes microplastics formed from synthetic polymers - mainly carbon - chain polymers - that can take hundreds of years to completely degrade [6].

Due to the prolonged decomposition time of the second group, their accumulation in the environment is steadily increasing, leading to escalating pollution of ecosystems [7]. It has been 20 years since an article published in the journal Science highlighted the accumulation of small plastic fragments and fibers in the environment, introducing the term "microplastics." This sparked the emergence of an entirely new scientific field of research [8].

To date, more than 7,000 publications worldwide have addressed the topic of microplastics—their distribution in the environment, nature, and even within the bodies of animals and humans [9]. Currently, microplastics are defined as polymer particles that are 5 mm or smaller. Their global quantity continues to rise in correlation with increasing production of polymer materials [10].

The scientific community has yet to definitively determine the rate at which polymer-plastic waste degrades into microplastics, as this depends on the composition and structure of the plastics, as well as the environmental conditions in which they are found [11]. Likewise, the timeframe for microplastics to further break down into nanoplastics has not been established [12]. Microplastics and nanoplastics have already been detected in soil, water, and air, and their negative effects on ecosystems and the health of animals and humans are well documented [13]. According to forecasts, by 2040, microplastic emissions into the environment may more than double [14].

Using modern instrumentation, scientists have detected nanoplastics in the lungs, liver, kidneys, blood, and reproductive organs of both animals and humans, as these particles are capable of crossing the body's protective barriers [15]. Although micro- and nanoplastics are partly excreted through urine, feces, and the lungs, a portion of them accumulates in the body over time, negatively impacting healthy organs by causing inflammation, oxidative stress, immune responses, and genotoxicity [16].

At present, nanoplastics - particles smaller than 1 micron - pose a particularly pressing concern. These particles are nearly invisible under a light microscope and require complex, expensive, and still underdeveloped methods for detection. The health impacts of nano- and microplastics remain under active investigation, but some of their potential adverse effects have already been identified. In particular, micro- and especially nanoscale plastic particles can penetrate and accumulate inside the body's cells, leading to inflammation and other harmful effects [17].

One of the main issues with micro- and nanoplastics is their accumulation in the body due to their lack of biodegradability [18]. Today, modern society cannot imagine life without plastics. They have infiltrated nearly every aspect of our daily lives [19].

Synthetic polymers and plastic products are produced in enormous quantities, and they are virtually non-biodegradable. Over hundreds of years, their waste contributes to the formation of micro- and nanoplastics [20]. Society’s dependence on polymer products continues to grow and is expected to increase further. While global synthetic polymer production was 2.3 million tons in the 1950s, by 2015 it had reached 448 million tons. Forecasts suggest this figure could double by 2050 [21].

According to the International Union for Conservation of Nature, 3.2 million tons of micro- and nanoplastics are generated annually in the environment. As of now, there is no clear or cost-effective method for collecting micro- and nanoplastics that have already entered the environment [22].

Modern Approaches to Reducing the Formation and Disposal of Micro- and Nanoplastics

It appears that the primary strategy is prevention and control of micro- and nanoplastic formation [21].

Initial efforts have already emerged in the field of micro- and nanoplastic disposal. In particular, bacteria have recently been discovered that produce enzymes capable of breaking down certain plastics. However, practical application of these enzymes remains distant, as their advantages and disadvantages still need to be fully understood. Scientists have already managed to increase the efficiency of these enzymes under laboratory conditions [5].

What are the pathways to mitigate the negative impact of polymer-plastic waste and micro- and nanoplastics on ecosystems and human health, given that these pollutants are already present in soil, air, and water [23]? The following measures are necessary:

- Widespread implementation of separate collection and sorting of plastic waste by composition, followed by processing methods that do not harm ecosystems or human health [8];
- Extending the "life cycle" of polymer-plastic products by reusing them whenever possible [24];

- Developing new technologies to recycle complex, non-reprocessable polymer-plastic waste with intricate chemical compositions [25];
- Creating methods for breaking down polymer-plastic waste into their original monomers and components [26];
- Developing technologies to convert polymer-plastic waste into energy sources [27];
- Designing new filtration systems capable of capturing microplastics from water and air [28].

To reduce the volume of polymer-plastic waste and the formation of micro- and nanoplastics, it is essential to develop polymer materials and products based on natural polymers, their derivatives, and synthetic heterochain polymers that are biodegradable [29].

Additionally, the production of single-use polymer products (such as disposable tableware) and synthetic polymer-based packaging materials should be banned or significantly reduced [30].

Measures to Protect Human Health from the Effects of Micro- and Nanoplastics

In terms of protecting human health [31], the following actions are necessary:

Develop standardized scientific methods for the detection, identification, and quantification of micro- and nanoplastics;

Given the potential for micro- and nanoscale plastic particles to accumulate in living organisms, it is essential to intensify research and implement the use of biodegradable polymers, especially in the food industry [32].

Micro- and nanoplastics, which result from the slow degradation of polymer "waste" in natural environments, are currently a major source of ecosystem pollution. Their presence is increasing and will inevitably continue to grow. Even if all sources of plastic waste in the environment were eliminated today, the amount of existing micro- and nanoplastics would still be significant enough to enter the human body [8].

Currently, there are three primary pathways by which micro- and nanoplastics enter the human body: air, water, and food [9].

Air: Micro- and nanoplastics enter the air as polymer-plastic waste decomposes in nature and landfills, and through soil erosion caused by wind [33].

Water: Water is one of the most significant global sources of micro- and nanoplastics. These particles have been detected in nearly all bodies of water - including oceans, seas, rivers, and even bottled drinking water [34].

Food: Another major pathway for micro- and nanoplastic intake is through food consumption [35].

Possible Methods for Detection and Quantitative Analysis of Micro- and Nanoplastics

Today, the presence of micro- and nanoplastics has been detected in nearly all types of food products, including fish, seafood, agricultural produce, fruits, water, and more [36].

However, no maximum permissible concentrations of micro- and nanoplastics have yet been established for the bodies of animals or humans [37].

To determine safe exposure limits for micro- and nanoparticles in the body, it is essential first to assess their actual concentrations and quantities in drinking water [38].

It has been shown that boiling drinking water can reduce the content of micro- and nanoplastics by up to 84%. Depending on the original water hardness (carbonate content ranging from 60 to 300 mg/L), micro- and nanoplastic levels decrease by 25% to 84%. During boiling, plastic particles bind with calcium carbonate and settle as sediment [39].

In addition to the ecological threat posed by polymer-plastic waste, micro- and nanoplastics are increasingly recognized as a serious health concern for humans [40].

Between 2013 and 2023, over 12,000 scientific publications have been registered on the topic of micro- and nanoparticles [41].

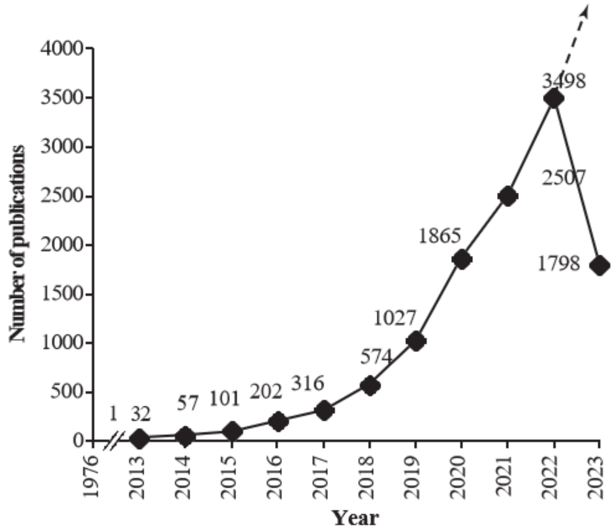

Figure 1. *Scientometric trend (number of publications) devoted to the problem of micro- and nanoplastics (the results for 2023 have not been summed up) [41]*

The development of reliable, highly sensitive methods for the identification and quantitative analysis of micro- and nanoplastics is essential for addressing the challenge of monitoring and regulating their presence in the human body [42].

Due to the extremely low concentrations and small sizes of synthetic polymer particles - including micro- and nanoplastics - in complex natural matrices such as biopolymers and food products, there are currently no standardized, reproducible methods that can provide accurate results.

Toxicological studies have identified micro- and nanoplastics as a potential health risk to humans [43, 44].

Analyses of hundreds of food products have confirmed the presence of microplastics, particularly those based on carbogenic synthetic polymers [45].

Below, we present a rationale for methodological approaches to the identification and quantitative analysis of microplastics in various materials, based on a comprehensive review of current literature.

Filtration and Extraction Methods for Micro- and Nanoplastics from Liquid Media

One of the simplest methods for isolating microplastics from liquid media is filtration. The efficiency of microplastic extraction from solutions depends on both the particle sizes and the pore size of the filtering material. Using membranes with pore sizes of 0.7 µm and 0.1 µm, researchers were able to filter out 31 and 182 particles per liter, respectively, from white wine [46]. However, microplastics filtered through membrane filters are difficult to extract due to their adhesion to the filter material.

Reliable results for the isolation of microplastics from bottled water were obtained by filtering through polymeric filters coated with a thin layer of aluminum [47].

A number of filter materials with various compositions are known to retain microplastics in the range of 10 to 0.1 µm [48–50]; however, recovering microplastics from these filters remains a challenge.

Density-Based Fractionation Methods for Micro- and Nanoplastics

The principle of microplastic separation by density is based on the difference between the density of the plastic particles and the liquid medium used. In this process, microplastic particles sediment within the liquid depending on their density. By varying the density of the liquid medium in the range of 1.0 to 1.96 g/cm^3, researchers have successfully fractionated microplastics across a broad range of densities [40, 48, 51–53].

This method enables the classification of microplastics by type, as different polymers possess characteristic density ranges. For example:

Polypropylene (PP): ~0.90 g/cm³
Polyethylene (PE): ~0.94 g/cm³
Polystyrene (PS): ~1.05 g/cm³
Polyvinyl chloride (PVC): ~1.40 g/cm³
Polyethylene terephthalate (PET): ~1.38–1.41 g/cm³
The results of microplastic fractionation by density are shown in Figure 2.

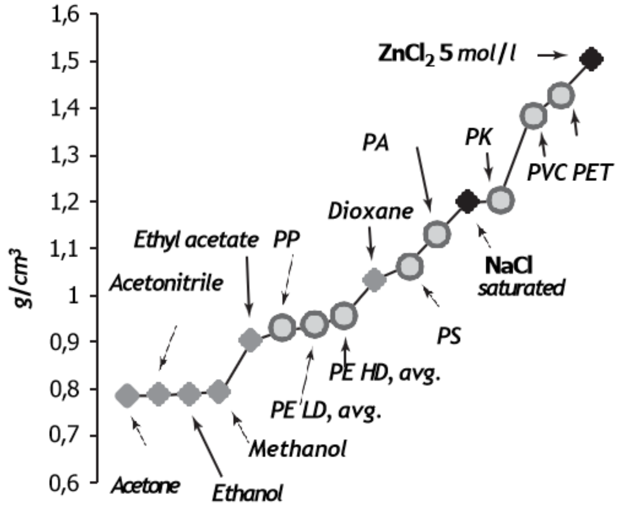

Figure 2. *The principle of microplastic fractionation in salt solutions and organic solvents with different densities [40]*

PA – polyamide; PC – polycarbonate; PP – polypropylene; PE HD –high-pressure polyethylene; PE LD – low-pressure polyethylene; PET – polyethylene terephthalate; PS – polystyrene; PVC – polyvinyl chloride.

This method is based on the mechanical separation of microplastics according to their morphological characteristics, followed by spectral or chemical identification. Microplastics in the particle size range of 0.05–0.5 mm can be analyzed using binocular or optical microscopes [40]. However, this method is not suitable for detecting nanoplastics due to their "invisibility" at the optical level and the tendency for nanoplastics to become electrically charged [54].

Methods for Destruction of Biological Matrices to Isolate Micro- and Nanoplastics

When determining microplastics contained in biological matrices of animal and plant origin (such as vegetables, fruits, meat products, milk, etc.), the process requires quantitative destruction of biopolymer matrices to a water-soluble state. This must be done using reagents that do not dissolve the microplastics and do not significantly alter their surface properties [40,44]. Such destructive agents include acids and their mixtures [48,55], alkalis [56,57], mixtures of hydrogen peroxide with nitric acid [58], and salts of divalent iron [59].

The preservation of microplastics is achieved during matrix degradation using enzymes such as cellulase and microbial proteases at low temperatures [60].

Extraction of Nanoplastics from Matrices

The methods described above are unsuitable for nanoplastics due to their small size and increased solubility and adsorption properties. Concentration and extraction of nanoplastics from liquid media can be performed using methods such as ultrafiltration [61], ultracentrifugation [62], and solvent evaporation [63]. A promising method for extracting nanoparticles is flow fractionation, where the perpendicular force acting on the nanoparticles within the flow is utilized. Depending on the diffusion coefficient, which is determined by characteristics such as size, shape, and density, particles are retained in the device's channel for varying amounts of time and can be separated [64].

Identification, Qualitative and Quantitative Analysis of Micro- and Nanoplastics Using Other Methods

Light Microscopy

Light microscopy has shown the potential for identifying and counting microplastic particles on filters where precipitation has occurred [44]. Reliable results were obtained for microplastic particles sized 0.5 mm and above. However, the error rate for identifying microplastics using light microscopy exceeds 20% [43] and sometimes reaches up to 70% [65]. Given this, light-optical microscopy can be used as a preparatory stage for microplastic analysis [41].

Electron Microscopy

Scanning electron microscopy (SEM) allows for the precise identification of size, shape, and surface morphology of microplastics [66]. To determine the chemical composition of microplastics, SEM is combined with energy-dispersive X-ray spectroscopy [43] or X-ray photoelectron spectroscopy [44]. SEM can achieve a practical resolution of 0.1 µm, making it suitable for investigating not only microplastics but also certain nanoplastic samples [62, 67]. There are limited reports on the use of transmission electron microscopy (TEM) for analyzing the composition of micro- and nanoplastics [68].

Infrared Fourier Spectroscopy

This is one of the most widely used methods for identifying, analyzing the structure, and quantifying microplastics [69]. The main limitation of this method is the presence of even trace amounts of water in the samples, as the strong and broad vibration bands of the O-H bonds in the water molecule can obscure much of the spectral range required for analysis [70]. Additionally, special requirements exist for the infrared transparency of substrates. There are reports on the use of infrared-transparent filters made of silicon [51], aluminum oxide [71], or zinc selenide [72].

Raman Spectroscopy

Raman spectroscopy allows for the identification of microplastic particles with sizes smaller than 20 µm [73,74], where deep dehydration of samples is not required due to the low sensitivity of the spectra to interference from -OH groups in water. The time required to record a single Raman spectrum is relatively long and may require manual pre-selection of microplastic particles [75]. By combining Raman micro-spectrometry with chemical analysis, pyrolysis chromatography, and mass spectrometry, reliable results can be obtained [54].

Other Methods

In addition to the methods mentioned above for identifying micro- and nanoplastic particles, other techniques include pyrolytic gas chromatography [41,44,54], thermal analysis methods [76,77], liquid chromatography [78], and more.

Unresolved Problems in the Identification of Micro- and Nanoplastics

Despite the rapid development of analytical technologies, the identification and quantification of micro- and nanoplastics remain among the most challenging analytical tasks in environmental science. Several unresolved problems continue to limit the reliability, comparability, and reproducibility of research results in this area [48].

A major challenge is the absence of standardized sampling and preparation protocols. Currently, sampling procedures vary widely depending on the matrix (air, water, soil, or biota), equipment type, and pretreatment conditions. This lack of harmonization makes it nearly impossible to compare data between laboratories or establish global databases. For instance, sampling volumes, filter pore sizes, and digestion conditions are often selected arbitrarily, which may result in partial loss or overestimation of particles. Establishing internationally recognized standards for sample collection and handling is therefore critical to minimize contamination and ensure reproducibility [50].

Another significant issue involves sample contamination. Plastic materials are ubiquitous in laboratory environments from gloves and sample containers to filtration membranes - making cross-contamination almost inevitable. Airborne synthetic fibers are also a frequent source of false positives. Although blank controls and clean-air facilities can reduce this risk, the problem remains unresolved and requires the development of robust contamination control procedures and certified reference materials [70].

Detection sensitivity for nanoplastics represents an even more complex problem. Nanoplastics (<1 μm) often escape conventional detection techniques due to their small size, low mass, and tendency to aggregate with natural colloids. Optical microscopy and vibrational spectroscopy are generally insufficient for nanoscale detection. While advanced tools such as flow field-flow fractionation, nanoparticle tracking analysis, and thermal desorption-pyrolysis-GC/MS have shown promise, they still lack the sensitivity, resolution, and throughput required for reliable environmental monitoring [62].

Furthermore, distinguishing plastic particles from organic or mineral particles in complex natural matrices remains difficult. The spectral features of aged or biofilm-coated plastics often overlap with those of natural polymers such as cellulose or chitin, leading to misidentification. This issue highlights the need for integrated, multi-technique analytical workflows combining spectroscopy, thermal degradation analysis, and microscopic imaging as well as the creation of comprehensive spectral databases that include weathered and biologically altered polymer spectra [77].

In summary, the main unresolved problems include (i) the lack of standardized sampling and analytical protocols, (ii) the risk of contamination and false detection, (iii) limited detection sensitivity for nanoscale plastics, and (iv) challenges in differentiating plastics from other particles. Addressing these limitations through international collaboration, development of certified reference standards, and harmonized analytical frameworks is crucial for advancing accurate, reproducible, and globally comparable assessments of micro- and nanoplastics in the environment.

Conclusions

This review highlights the growing environmental and health threats posed by micro- and nanoplastics and summarizes existing analytical and mitigation approaches. The literature demonstrates that while substantial progress has been achieved in identifying and characterizing micro- and nanoplastics, serious methodological and regulatory gaps persist.

The findings confirm that micro- and nanoplastics originate from multiple anthropogenic sources, including packaging materials, textiles, industrial effluents, and the degradation of macroplastic waste. Their persistence in natural environments contributes to bioaccumulation in aquatic and terrestrial organisms, ultimately threatening human health through the food chain. Therefore, understanding the sources, pathways, and behavior of these particles is essential for designing effective mitigation and regulatory strategies.

At present, analytical research is primarily focused on improving detection and quantification methods. However, to ensure a comprehensive approach, greater emphasis must be placed on prevention, environmental monitoring, and global standardization efforts. Developing biodegradable alternatives to conventional plastics, enforcing stricter waste management policies, and implementing extended producer responsibility systems are among the most promising directions for reducing micro- and nanoplastics generation. Additionally, the integration of biotechnological solutions, such as plastic-degrading microorganisms and enzyme-based degradation systems represents an emerging frontier in this field.

Future work should focus on:

establishing harmonized sampling and analytical standards;

developing high-sensitivity tools for nanoscale detection;

assessing long-term ecological and toxicological impacts of micro- and nanoplastics;

promoting circular economy principles to minimize plastic leakage into the environment and so on.

In conclusion, bridging the gap between analytical progress and practical mitigation strategies requires coordinated global action. Advancing scientific understanding, policy integration, and sustainable material innovation will be vital to mitigating the ecological and health consequences of micro- and nanoplastics.

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