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FROM CORRECT WASTE MANAGEMENT TO HEALTH PROTECTION: A FOCUS ON NANOTOXICS

Gea Oliveri Conti [1,2,3,*], Marco Dettori [4], Carmen Sica [1,5], Maria Castrogiovanni [1,5], Paola Rapisarda [1,5], Eloise Pulvirenti [1,2] and Margherita Ferrante [1,3,6]

[1] *Department of Medical, Surgical and Advanced Technologies "G.F. Ingrassia", University of Catania, Santa Sofia 87, 95123, Catania, Italy*
[2] *ISDE, International Society of Doctors for the Environment, Regional Section - Sicily, via XXV Aprile, 34, 52100 Arezzo, Italy*
[3] *NANOMED - Research Center on Nanomedicine and Pharmaceutical Nanotechnology, Department of Drug and Health Sciences, University of Catania, via Valdisavoia 5, 95123 Catania, Italy*
[4] *Department of Architecture, Design and Urban planning, University of Sassari, Palazzo del Pou Salit, Piazza Duomo 6, 07041 Alghero, Italy*
[5] *PhD Course on Earth and Environmental Sciences of Department of Biological, Geological and Environmental Sciences, Corso Italia 57, 95129 Catania, Italy*
[6] *Interdepartmental Research Center for the Implementation of Physical, Chemical, and Biological Monitoring Processes in Aquaculture and Bioremediation Systems, University of Catania, Santa Sofia 87, 95123 Catania, Italy*

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ABSTRACT
Waste generation has increased drastically worldwide in recent decades. Less than 20% of waste is recycled each year, and one-third of all food is wasted. While a fair level of knowledge exists concerning the general risks, there are notable gaps in understanding specific aspects of human health risks related to improper waste disposal and recycling, such as plastics in all types of wastes, and metallic nanoparticles from urban and sanitary wastewater, representing both emerging pollutants with a broad range of human health impacts. Although general environmental risks associated with waste mismanagement are well recognized, significant knowledge gaps persist regarding the specific human health impacts linked to emerging particulate pollutants. In particular, microplastics and metallic nanoparticles represent critical contaminants of growing concern due to their persistence, mobility, and broad toxicological profiles. This narrative review synthesizes the current scientific understanding of microplastic and metallic nanoparticle pollution, particularly through urban and sanitary wastewater, their toxicological profiles, and the limitations of current recycling and circular economy strategies in addressing these issues. It examines the environmental occurrence, release pathways, and health effects of these particles, highlighting how improper waste disposal, recycling processes, and wastewater treatment inefficiencies contribute to their dispersion. The findings highlight the need for innovative waste treatment technologies and a more comprehensive approach to risk assessment, particularly within life cycle assessments (LCA). Overall, the review underscores the urgency of integrating particle-specific metrics into monitoring frameworks and LCA methodologies to better protect environmental and human health.

1. INTRODUCTION

Over the past two centuries, humanity's relationship with waste has undergone a radical transformation. With the Industrial Revolution and the urban expansion of the 19th century, waste production began to grow far beyond the capacity of communities to dispose of it sustainably. In the 20th century, the introduction of plastics and synthetic materials further worsened the situation, marking the shift from predominantly organic and biodegradable waste to durable and persistent waste (Alanalp et al., 2026). Globally, waste management has become one of the most urgent environmental challenges, particularly in rapidly developing countries where infrastructure struggles to keep pace with demographic and industrial growth. Despite regulatory efforts introduced in many nations since the 1970s, the amount of waste continues to increase, along with the associated risks to the environment and human health (Ye et al., 2014).

The improper waste management, recycling, and discharge of wastes in the environment contribute to the environmental health impacts at the water, soil, and air levels,

* Corresponding author:
Gea Oliveri Conti
email: olivericonti@unict.it

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but with evidence of human health negative effects (Raphela et al., 2024).

Just in Japan, the World Bank has forecasted a rise of 1.3 - 2.2 billion tonnes of waste generated yearly by 2025, highlighting that 50% of waste will be collected, and inefficient management service will leave the area polluted, while the rest of the uncollected waste will be discarded (UN Environment, 2017).

Globally, the problem concerns not only the quantity but also the nature of waste. In recent years, the issue of invisible waste, such as microplastics, has emerged strongly. These originate from a variety of sources, including synthetic clothing, cosmetics, and the degradation of plastic materials. The lack of sufficiently advanced and effective water and wastewater treatment technologies has facilitated the spread of these micro- and nanoparticles in the environment (Cristaldi et al.,2020).

As by-products of both improper waste management and the current absence of efficient water treatment technologies, the large releases in environment of microfibers and microparticles are recognized as a physical risk and concern. Between the last, micro- and nanoplastic particles and nanometallic particles represent the last emergent pollutants, discovered in all environments and already affecting the food chain with several concerns for human health (Garrido Gamarro & Costanzo, 2022).

Considering this evidence, it becomes urgent to adopt more sustainable and integrated approaches to waste management, which should include not only efficient collection and recycling, but also source prevention, technological innovation, and greater social awareness of the issue (Figure 1).

2. METHODOLOGY OF REVIEW

The methodology of this review involved a narrativeand structured search of the scientific literature to capture the most recent and relevant studies related to microplastics, metallic nanoparticles, wastewater contamination, toxicity, and circular economy approaches. We searched multiple authoritative databases, including PubMed, Scopus, and Web of Science, covering publications from January 2010 to January 2026 to include contemporary research and emerging trends. The search strategy combined keywords such as "Waste management", "emergent pollutants", "Microplastics", "Metallic Nanoparticles", "Risk assessment", "Health impacts", and "Prevention", using Boolean operators to refine the results.

We focused on original articles published in English that addressed the environmental occurrence, fate, transport, and toxicological effects of micro- and nanoparticles, as well as studies describing advances in wastewater treatment technologies and waste management practices relevant to these contaminants. Additionally, papers discussing circular economy strategies and policies for mitigating waste and emerging pollutants were included. The review encompassed a broad range of study types, including observational and experimental research, in vitro and in vivo toxicity assessments, modeling studies, and comprehensive review articles.

To ensure the quality and relevance of the included literature, we excluded non-peer-reviewed publications such as conference abstracts, theses, and non-scientific reports, as well as studies that focused exclusively on macroplastics without addressing micro- or nanoparticles. Publications outside the 2010-2024 timeframe were generally excluded, except for seminal or highly cited works considered essential for contextual understanding.

3. MICROPLASTICS RELEASED BY IMPROPER WASTE MANAGEMENT OR RECYCLING

Microplastics released due to improper waste management or recycling represent one of the main contemporary environmental issues.

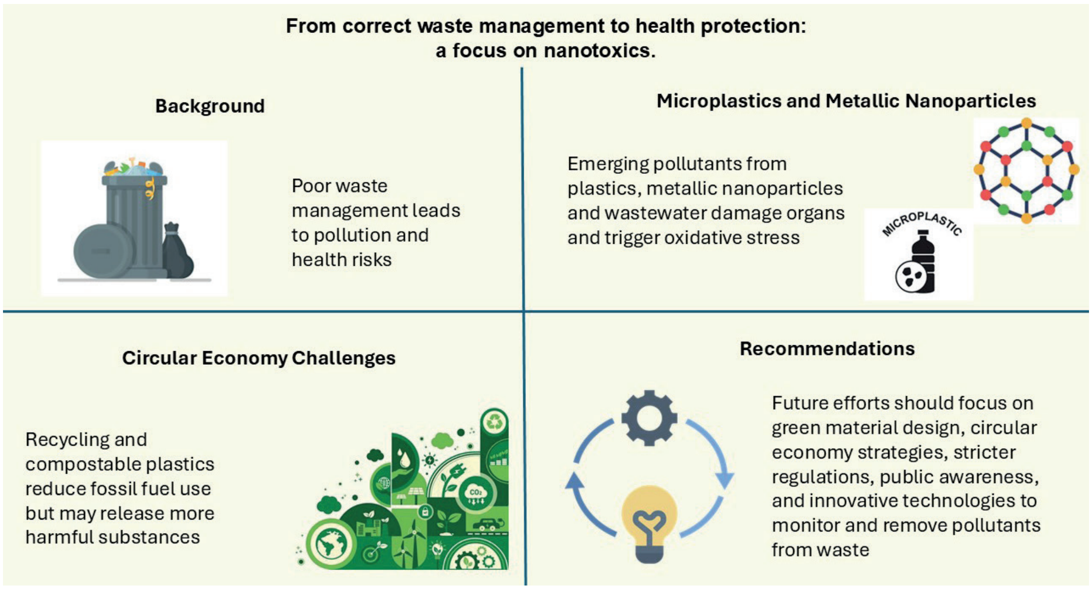

FIGURE 1: Emerging pollutants and health risks in circular waste management.

Plastics are acknowledged as emergent persistent pollutants that are capable (non-biodegradable) of causing contamination for extended periods in all environmental matrices. The plastic polymers produce small fragments or particles through crushing, splitting, and degrading during use. Microplastics refer to plastic fragments and particles with a diameter of less than 5 mm. They are called nanoplastics when the diameter is less than 1 µm (Oliveri Conti et al., 2024). Microplastics (primary microplastics) are also voluntarily produced and added to personal care products such as facial cleansers and cosmetics, hence contributing to wastewater in output effluents rich in microplastics.

According to the United Nations Environment Programme (UNEP, 2024), an estimated 19-23 million tonnes of plastic waste are dumped into aquatic ecosystems each year, contaminating lakes, rivers, and seas. In recent decades, numerous studies have documented a progressive increase in the presence of microplastics in the environment. For instance, Lebreton et al. (2017) highlighted how rivers are releasing increasing amounts of plastic into the oceans, reflecting a rise in global plastic production and ineffective waste management (Lebreton et al., 2017). In marine contexts, research by Cózar et al. (2014) in the Pacific Ocean documented a consistent increase in microplastic concentrations, demonstrating that plastic dispersion in the oceans is a continuously growing phenomenon (Cózar et al., 2014). Even in more sensitive environments, such as the Persian Gulf, increasing microplastic concentrations have been observed, as shown by Kor K & Mehdinia A., 2019, confirming the global spread of this issue (Kor K & Mehdinia A., 2019). A review by Eerkes-Medrano et al. (2019) highlighted that freshwater systems are also experiencing a significant increase in microplastic presence (Eerkes-Medrano et al., 2019), and a recent study further supports this alarming trend, documenting the widespread presence of microplastics across various freshwater compartments, including water columns, sediments, and aquatic biota (Ashamo et al., 2026), indicating that plastic pollution is pervasive across both marine and freshwater ecosystems. Similarly, studies on atmospheric microplastic pollution have shown a significant rise in the deposition of synthetic fibers in the air, suggesting that microplastic contamination affects not only aquatic but also terrestrial environments (Dris et al., 2016). Taken together, these findings illustrate a multi-compartment dispersion of microplastics across water, air, and sediments.

This dispersion not only alters natural habitats but also undermines the ability of ecosystems to adapt to climate change, directly and indirectly contributing to global warming and, consequently, affecting the health of millions of people (Oliveri Conti et al., 2024).

The exposure to microplastics induces a variety of toxic effects, including oxidative stress, metabolic disorder, immune response, neurotoxicity, as well as reproductive and developmental toxicity (Pulvirenti et al., 2022).

Several studies showed the presence of microplastics and nanoplastics in the brain, kidney, lung, liver, blood, heart, etc. The exposure is due to inhalation, dermal absorption, and ingestion. Also, due to the surface energy caused by their small size, microplastics may act as the vector adsorbing other environmental pollutants, especially heavy metals and hydrophobic organic chemicals (HOCs), which may enhance their toxicity (Xiang et al, 2022).

According to the last studies, several foods are already contaminatedby environmental microplastics, including marine and terrestrial food sources, as well as drinking waters (Garrido Gamarro & Costanzo, 2022; Ferrante et al., 2022; Oliveri Conti et al., 2020).

In this context, the first results from the Italian PRIN-PNRR project AQUApLASt (P2022XE857 – Tap wAter QUality and microplAstics. Countering an ecoLogical threAt with an evidence-baSed approach) assessed microplastic contamination in drinking waters of Catania and Sassari, representing two major urban centers of southern Italy's largest islands. The study revealed microplastics (<10 µm) in tap water at a mean concentration of 4.85×10^6 particles/L in Catania (95% CI: 2.04×10^7 - 8.44×10^7; mean diameter: 3.2 µm), and 6.54×10^6 particles/L in Sardinia (95% CI: 8.16×10^5 - 6.54×10^6; mean diameter: 1.8 µm). Although these levels are lower than those reported in bottled mineral water (3.16×10^{10} particles/L; Zuccarello et al., 2018), the findings raise concerns regarding chronic exposure from tap water sources, especially when superficial waters are used, despite undergoing more advanced treatments than deep-water sources. Notably, particles <2 µm are considered the most hazardous due to their heightened toxicological potential (Oliveri Conti et al., 2024).

The recycling of plastic waste is not the cure. In fact, the toxicity of methanolic extracts obtained from compostable plastics (BPs) and conventional plastics (both virgin and recycled) showed an elevated toxicity of recycled plastics, compostable plastics, and semi-degraded compostable plastics resulting from partial disintegration, as compared to virgin conventional plastic extracts (Wang et al., 2023). The potential hazards that arise from the recycling processes of plastics derive from previous use and the recycling process itself, and from the release of the highest number of microplastics.

Despite the current and innovative technologies to recycle plastic waste, non-recoverable nanoplastics and microplastics cannot easily catch up with existing reclaim or treatment technologies due to their exceptionally small size. Further, the size reduction and washing during mechanical recycling facilities cause the release of a significant quantity of microplastics into the environment, reaching water or air as microplastics from recycling facilities. A study on PET recycling facilities reveals microplastic releases range from approximately 23-1836 mg/L in wastewater, distributed in the effluent (8-83 mg/L) and the sludge (52,166-68,866 mg/L) of the facility (Singh & Walker, 2024).

4. METALLIC NANOPARTICLES RELEASED BY IMPROPER WASTE MANAGEMENT

Metallic nanoparticles are nanomaterials constituted only by one element, such as Au, Ag, Pt, Cu, Ti, Pd, Re, Zn, Ru, Co, Cd, Al, Ni, and Fe. Metallic nanoparticles have remarkable properties, including surface plasmon resonance, high reactivity, and broad electromagnetic spectrum absorption. Currently, metallic nanoparticles are applied in several areas, including electronics, textiles, industry, healthcare, biomedicine, environment, agriculture, and food. Metallic nanoparticles, also, are also used for several applications due to their catalytic, antimicrobial, and finally, cancer and viral therapy characteristics.

Given their widespread use and unique physicochemical properties, their release into the environment has become increasingly relevant.

Increasing amounts of engineered nanoparticles in wastewater can reach the aquatic environment by passing through sewage treatment plants.

So, metallic nanoparticles were components of sanitary and urban wastewaters that contribute through wastewater facilities' output effluents and sewage sludge to discharge these in the environment, reaching the human organs through diet and dermal absorption (Shahalaei et al., 2024; Cervantes-Avilés & Keller, 2021).

These pathways highlight how both domestic and industrial activities contribute to the continuous introduction of metallic nanoparticles into natural systems.

Unlike traditional dissolved heavy metals, engineered metallic nanoparticles exhibit greater mobility and enhanced ability to penetrate cellular membranes due to their nanoscale size and unique surface properties (McGinnity TL et al., 2021). This increased bioavailability allows them to interact more readily with biological tissues, influencing their environmental and biological behavior.

Moreover, their persistence in the environment is often greater than that of conventional pollutants, as they can resist degradation and accumulate in sediments and organisms (Zhao et al., 2021).

Fe or Zn particles holds good potential to act as reducing agents relative to many redox-labile contaminants, and these has been successfully applied in the removal of a large range of wastewater and drinking water contaminants, including halogenated organic compounds, organic dyes, phenols, heavy metals, inorganic anions such as phosphates and nitrates, metalloids, and radio elements (Lu et al.2015).

Their reactivity, while beneficial in engineered applications, also influences their environmental behavior and interactions with pollutants.

In comparison to microplastics, which primarily act as physical carriers of pollutants and can cause mechanical harm to aquatic life, metallic nanoparticles pose chemical toxicity risks through the release of reactive metal ions and the generation of oxidative stress within cells. Pesticides, while biologically active, usually degrade over time or can be broken down by microbial action; metallic nanoparticles, however, can remain stable and continue to exert toxic effects long after their initial release.

Metallic nanoparticles challenge conventional wastewater treatment processes. Unlike dissolved metals, which can be precipitated or adsorbed by standard treatments, nanoparticles often pass through filtration and sedimentation systems due to their small size and colloidal behavior. This unpredictability complicates risk assessment and calls for the development of advanced treatment technologies specifically targeting nanoparticle removal (Azeez et al., 2023).

As a result, significant fractions of these particles can bypass treatment barriers and enter natural waters.

Metallic nanoparticles can induce ecotoxicological effects due to their specific chemical properties, reaching through the water and food chain to the human body, exerting several health effects.

Therefore, metallic nanoparticles can be translocated through the circulatory, lymphatic, and nervous systems to many tissues and organs, including the brain and placenta. Toxic effects encompass tissue inflammation and alter cellular redox balance toward oxidation, leading to abnormal function, DNA mutation, or cell death (Medici et al., 2021).

These biological interactions underscore the potential for both acute and chronic health impacts.

Among the emerging technologies for the removal of metallic nanoparticles from wastewater, nanoporous materials and selective membranes are showing promising results. These advanced filtration systems are designed to capture particles at the nanometer scale through size exclusion and specific surface interactions. Functionalized bioadsorbents, engineered to bind selectively to metal nanoparticles, offer an eco-friendly alternative by enhancing the efficiency of contaminant removal without generating secondary pollution (Nguyen et al., 2023) (Figure 2).

Moreover, bioremediation approaches using selected microorganisms are gaining attention as sustainable solutions. Certain bacteria and fungi have demonstrated the ability to adsorb, transform, or even degrade metallic nanoparticles, reducing their toxicity and mobility. These biological treatments could be integrated with conventional methods to improve overall removal rates and mitigate environmental release, paving the way for greener and more cost-effective wastewater management strategies (Alavi et al., 2022).

Together, these technologies provide additional approaches that may help address some of the limitations of conventional treatment systems.

5. LIFE CYCLE ASSESSMENT LIMITATIONS IN EVALUATING PARTICULATE POLLUTANTS FROM WASTE MANAGEMENT

Life Cycle Assessment (LCA) is a widely adopted methodology for evaluating the environmental impacts associated with products and processes across their entire life cycle, from raw material extraction to end-of-life management. Although LCA is a powerful decision-support tool, its application to contaminants such as microplastics and metallic nanoparticles remains limited by substantial methodological gaps (Nizam et al., 2021). Current LCA frameworks are primarily designed to quantify mass flows, emissions, and resource use, but they struggle to incorporate particulate pollutants whose release is diffuse, non-linear, and strongly dependent on mechanical, chemical, and biological transformations occurring along the waste management chain (Salieri et al., 2018). Moreover, the absence of standardized characterization factors for particle-specific impacts, such as persistence, bioaccumulation, and ecotoxicity, prevents a comprehensive assessment of their environmental burden. A notable limitation in several

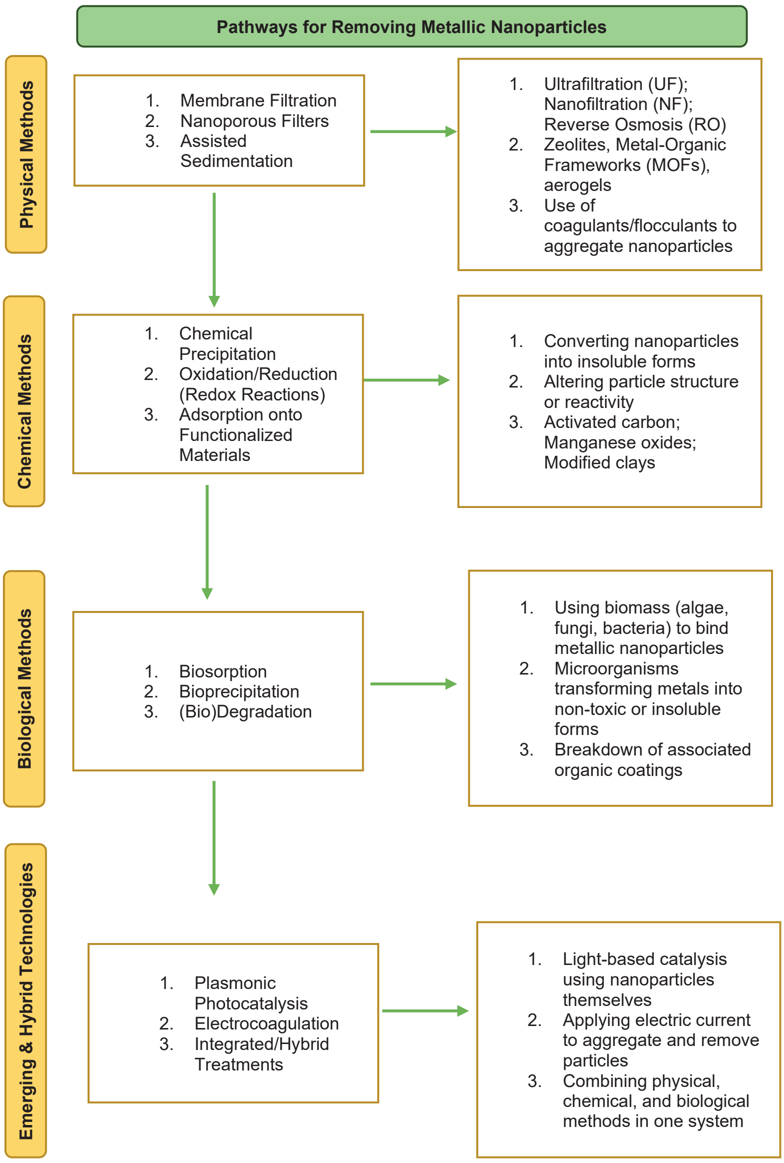

FIGURE 2: Pathways for removing metallic nanoparticles.

standard LCA methodologies lies in omitting the long-term fate of chemicals and particulates released during waste treatment and recycling processes (Singh et al., 2024).

In the case of microplastics, most LCAs of plastic recycling processes do not account for the generation of secondary micro- and nanoplastics during mechanical treatments such as shredding, washing, and extrusion (Rafiq et al., 2023). Plastic recycling shows both positive and negative aspects: while it significantly reduces fossil fuel utilization, power consumption, and landfilling, the size reduction and washing steps in mechanical recycling facilities cause the release of substantial quantities of microplastics into wastewater and air. As a result, the environmental benefits attributed to recycling may be overestimated, since the release of microplastics into wastewater streams or air emissions is rarely quantified or included in impact categories (Gandhi et al., 2021). The omission of short-term LCA studies in disregarding the consequences of chemical and particulate releases raises concerns about the overall efficacy of plastics recycling as a solution to plastic pollution (Table 1).

For metallic nanoparticles, the main limitation lies in the lack of LCA studies addressing their accumulation and fate in wastewater sludge destined for agricultural reuse or energy recovery. Despite the increasing evidence of nanoparticle accumulation in sludge, the absence of short-term LCA studies evaluating their concentrations in wastewater and biosolids raises concerns about the overall efficacy of sludge recycling as a sustainable waste management strategy. Unlike plastic recycling, where the concern is the mechanical fragmentation of polymers, the critical issue for metallic nanoparticles is their persistence in biosolids and their potential mobilization during sludge application to soils (Kim et l., 2010).

Overall, the current LCA framework is not yet equipped to fully capture the environmental implications of particulate contaminants generated or mobilized during waste management processes (Bisinella et al., 2024). Developing

TABLE 1: Plastic recycling, alternatives, and the circular economy each offer unique benefits and challenges in reducing plastic pollution.

	Main Features	Advantages	Disadvantages
Plastic Recycling	Processing used plastic into new materials.	• Reduces waste and pollution • Saves energy and raw materials	• Not all plastics are recyclable • Costly and energy-intensive - Downcycling issues
Plastic Alternatives (Biodegradable, Compostable, Bio-based, Reusable)	Use of biodegradable, compostable, or plant-based plastics.	• Break down faster in specific conditions • Useful for short-term use (bags, cutlery)	• Often requires industrial composting • May compete with food production • Not marine-safe
Circular Economy	A system focused on reuse, repair, recycling, and sustainable product design.	• Reduces overall waste • Encourages innovation and durability • Less resource extraction	• Requires systemic change • Initial implementation can be complex and costly

particle-specific inventory data, fate models, and characterization factors is essential to avoid underestimating the impacts of recycling strategies and to support more informed decisions in circular economy policies.

6. CONCLUSIONS

The widespread use of plastic and metallic nanomaterials has led to an increase in environmental exposure affecting human health. The alarming consequences of this rapid rise have begun to emerge.

Nanomaterials, often not classified as true pollutants, can be transported into the environment through water, accumulate in soil, and eventually enter the food chain. It is well known that nanotoxics generate oxidative stress in cells as a response to the reactive oxygen species and induce toxicity through inflammation.

Considering this, urgent measures must be taken to reduce the use and release of both microplastics and metallic nanoparticles into the environment. The emergence of new nano-pollutants poses a growing and tangible threat to public health and ecosystem stability. Although the circular economy offers a promising framework for sustainable resource management, it is currently insufficient to effectively prevent contamination by nanoscale pollutants. Due to their persistence and often invisible nature, these particles require targeted technological solutions that can safely and definitively remove them (Selim et al., 2025). Advanced technologies such as pyrolysis for plastics and specialized filtration systems for nanoparticles must be developed and implemented on an industrial scale. Moreover, LCA studies should systematically account for the environmental impact caused by pollutant release during waste recycling processes, in order to provide a more realistic and transparent evaluation of environmental balances.

Ultimately, addressing the issue of nano-pollutants demands an integrated approach that combines technological innovation, regulatory updates, social responsibility, and public awareness. Only through collective effort can we harness the benefits of nanotechnology while truly safeguarding human and environmental health.

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