Review

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Microplastics and nanoplastics: emerging threats to cardiovascular health – a comprehensive review

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Background: Global plastic production surged to 400.3 million metric tons in 2022, contributing significantly to environmental pollution. Projections estimate that 13.2 billion tons of plastic waste will be present in ecosystems by 2050. This increase in plastic production has led to substantial human exposure to microplastics (MPs) and nanoplastics (NPs). While their environmental and general health impacts are well-documented, the specific effects on cardiovascular health remain underexplored.
Objectives: This review aims to examine the presence of MPs and NPs in the environment, their routes of human exposure, and their toxicological implications for the cardiovascular system (CVS), focusing on oxidative stress, apoptosis, cardiac fibrosis, and major adverse cardiovascular events (MACE).
Methods: A comprehensive literature review was conducted using PubMed, Scopus, and Google Scholar. Relevant studies from the past 10 years were selected based on keywords like "microplastics," "nanoplastics," and "cardiovascular health."
Results: MPs and NPs are found in air, water, and food, entering the human body primarily through inhalation, ingestion, and dermal contact. These particles induce oxidative stress, mitochondrial dysfunction, and apoptosis, which impair cardiovascular health. MPs have been detected in arterial tissues, particularly in atherosclerotic plaques, correlating with increased MACE risk. MP exposure is linked to VC, reduced vessel flexibility, and increased thrombosis severity. Additionally, MPs contribute to inflammation and lipid metabolism disruption, which further exacerbate heart disease.
Conclusion: The evidence suggests a concerning link between plastic exposure and cardiovascular health, highlighting the urgent need for further research to understand the long-term effects of MPs and NPs on CVSs.

Keywords: atherosclerotic plaques, cardiovascular health, microplastics, nanoplastics, oxidative stress, plastic exposure

Introduction

Plastic production has surged over the past century, reaching an astounding 400.3 million metric tons across the globe in 2022, marking a 1.6% increase compared to the previous year [1]. This escalation is emblematic of the exponential growth witnessed in plastic manufacturing since the 1950s, which saw production skyrocket from a mere 1.7 million tons [2]. The ubiquity of plastics is underscored by the existence of approximately 45 distinct varieties, including polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET)[3]. Persisting production and waste management practices portend dire consequences, with projections indicating a staggering 13.2 billion tons of plastic waste in natural environments by 2050[4]. The alarming reality of plastic pollution is highlighted by the release of 12.7 million metric tons of plastic into oceans in 2010 alone[5], contributing to the accumulation of over 250,000 tons of abandoned plastics in marine ecosystems[6]. This pervasive contamination has introduced microplastics (MPs) and nanoplastics (NPs) into ecosystems and food chains, raising serious concerns about their implications for human health.

MPs and NPs are categorized as man-made polymers that are smaller than 5 mm and 100 nm, respectively[7]. These particles arise from the breakdown of larger plastic waste and direct release from consumer goods and industrial activities, existing in various forms such as fragments, fibers, beads, and films. Primary MPs are intentionally incorporated into commercial products or generated through the breakdown of larger plastic materials[8], while NPs are produced through the degradation of MPs or emitted from sources like electronics, paints, and adhesives[9]. The absorption and movement of MPs and NPs into food chains may impact human health and could present potential carcinogenic risks. These toxic compounds may lead to chronic health risks, including hormonal system disruption, such as endocrine disruption, as well as inducing mutagenicity and carcinogenicity[10]. A recent review demonstrated that MPs and NPs disperse and accumulate within organisms' circulatory systems, leading to significant impairment of cardiac and cerebral tissue function and triggering toxic microvascular alterations. Additionally, it underscored that factors such as particle diameter, modification, surface charge, and solution concentration influence the ability of MPs/NPs to

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stimulate platelet aggregation[11]. While previous research has explored the general toxicological effects of MPs and NPs on various organ systems, their specific impacts on cardiovascular health have received limited attention. Recent evidence suggests that MPs and NPs can accumulate in vascular tissues, inducing oxidative stress, mitochondrial dysfunction, and cardiac fibrosis.

Determining disease causation in population studies can be challenging, but experimental evidence shows a direct link between plastic chemicals, like BPA, and cardiac dysfunction by disrupting myocardial calcium signaling, a key regulator of electrical activity, contractile function, and vasoactivity[12]. This comprehensive review aims to examine the broad presence of MPs and NPs in various environments, their pathways of dispersion, and their detrimental cardiovascular effects. It details how these particles induce oxidative stress, mitochondrial dysfunction, apoptosis, and fibrosis in the cardiovascular system (CVS). The review further underscores the association between MPs in arterial plaques, thrombosis, and an elevated risk of major adverse cardiovascular events (MACE).

Methodology

A comprehensive literature review was conducted to collect and synthesize existing data on the environmental presence, dispersion pathways, and cardiovascular impacts of MPs and NPs. Databases including Scopus, PubMed, and Web of Science were searched using keywords such as "microplastics," "nanoplastics," "cardiovascular health," "oxidative stress," "fibrosis," "thrombosis," "inhalation," "ingestion," and "dermal exposure." Articles published were included to ensure the review covered recent advancements and findings. The inclusion criteria for studies were human studies published within the past 10 years, focusing on the effects of MPs and NPs on cardiovascular health, mortality, morbidity, and prevalence. Studies were excluded if they were not peer-reviewed articles or relevant gray literature, to ensure quality and reliability.

Results

Presence of MNPs in the environment

MPs and NPs disperse throughout the environment via runoff, atmospheric deposition, and direct release, accumulating in marine sediments, freshwater systems, soil, and even atmospheric aerosols. Secondary MPs and NPs, which arise from the fragmentation of MPs, represent roughly 80% of the overall plastic emitted into the environment, while primary MPs make up approximately 15–30% of the total amount[9]. More than 80% of MPs are generated on land, with contributions from wastewater, industrial operations, and natural erosion, whereas under 20% stem from marine activities[13]. Due to their small size, durability, and buoyancy, these particles can travel extensively across the globe, persisting in various ecosystems. The United Nations Environment Programme indicated that 275 million tons of plastic waste were generated in 2010, with approximately 4.8–12.7 million tons escaping into aquatic systems. This emphasizes the vast scale of plastic pollution and its potential for significant environmental repercussions[14].

Routes of MNPs entry into food chains

MPs and NPs have permeated the food chain through multiple routes, raising serious concerns regarding their effects on ecosystems and human health. These minute particles have been detected at the foundation of the food web, including in organisms like zooplankton, which play a crucial role in aquatic ecosystems[15]. This initial entry point indicates a wider spread throughout the food chain as larger predators ingest these contaminated organisms. MPs have been identified in various food products that humans commonly consume, including honey, beer, salt, sugar, seafood, and bottled water[16]. For example, a liter of bottled water contains approximately 240,000 minuscule plastic particles, with around 90% classified as NPs. This concentration represents a staggering increase of 10–100 times the number of plastic particles identified in prior research, which primarily concentrated on larger MPs[17]. These statistics illustrate the widespread occurrence of MP contamination in everyday products. Additionally, it is estimated that an individual consumes approximately 39,000–52,000 MPs each year through food and water, a figure that may rise to between 74,000 and 121,000 particles annually when considering inhalation[18].

The presence of MPs in seafood is particularly alarming due to bioaccumulation, where higher concentrations of plastics are found in organisms higher up the food chain, including those consumed by humans. This bioaccumulation process not only impacts marine organisms, resulting in negative health consequences such as microbiota imbalances, inflammation, and physiological disturbances, but also presents direct health hazards to humans who consume contaminated seafood. The ingestion of MPs can lead to gastrointestinal (GI) distress and other health issues, highlighting the intricate and pervasive impact of plastic pollution on the food chain.

Human exposure to MNPs

Inhalation

Ingestion, inhalation, and dermal contact represent significant routes of exposure of micro and nonoplastics (MNPs) to humans, posing potential health risks. Research has shown that particle inhalability depends on size and shape, with only particles smaller than 5 μm and fibrous particles likely to reach the deep lung[19]. A study using a Breathing Thermal Manikin found that humans breathe in airborne MPs, primarily polyester, indoors, where these particles make up about 4% of all inhaled organic particles. Cellulose particles were similarly common, while protein particles, likely from skin, were the most abundant. This study expanded detectable particle sizes down to 11 μm[20]. The sources of airborne MNPs include construction materials, synthetic textiles, road-wear particles, landfills, plastic abrasions, waste incineration, and sewage sludge[21]. MNPs have also been detected in indoor air, comprising approximately 4% of indoor airborne particulate matter[22], with individuals estimated to inhale up to 130 MNPs daily[23]. Industrial workers face increased susceptibility to MNP exposure. Particle aerodynamic size influences the depth of penetration within the respiratory system upon inhalation, with particles smaller than 2.5 μm posing heightened concern due to their increased likelihood of reaching alveolar sacs, where the process of gas exchange occurs[24].

Ingestion

The ingestion of MPs and NPs is the primary route of entering the human body[25]. Once ingested, these particles pass through the GI tract. While MPs are unlikely to permeate the GI tract at

a paracellular level due to the small size of the relevant pores, NPs can be absorbed through lymphatic tissue. They may enter the body via endocytosis or maybe phagocytosed by cells in the Peyer's patches[26]. In vitro studies on mice indicate that intestinal absorption of MPs is low, at about 0.04–0.3%[27], while the oral bioavailability of NPs, particularly those smaller than 50 nm, is significantly higher[28]. Within the GI tract, NPs can transform when they interact with various molecules, such as proteins and lipids that can influence their absorption. Although a substantial portion of existing research has focused on PS nanoparticles, it is crucial to also study other prevalent plastics like PP, PE, and PET due to their widespread amount in the environment. The complexities of understanding their effects on human health stem from the diverse physical and chemical properties of these particles, making them multifaceted stressors with significant implications for ecological and human health.

Dermal route

Dermal exposure, although deemed less significant, remains a potential route for MNP entry. A study proposed the 500-Da rule by examining the molecular weights of topical drugs and common contact allergens. It concluded that when a molecule's weight exceeds 500 Da, its absorption through human skin decreases significantly[29]. Another study on nanoparticle translocation across human skin concluded that particles up to 4 nm can cross intact skin, particles ranging from 4 to 20 nm can cross both damaged and intact skin, particles between 21 and 45 nm can cross only damaged skin, and particles over 45 nm cannot penetrate human skin[30]. Studies suggest that MNPs can permeate the skin, primarily sourced from microbeads in personal care products and synthetic fibers[31]. However, the concern regarding dermal exposure is diminishing as many countries prohibit microbeads in such products. The presence of MNPs in human diets, primarily through seafood consumption, raises significant health concerns. MNPs build up in the tissues of marine organisms, which may carry long-term health risks for consumers. MPs have also been identified in different sources, including table salt, and processed foods like bottled water and milk[32]. Furthermore, the presence of MNPs in drinking water, both bottled and tap, underscores the pervasive nature of plastic pollution. Consequently, MNPs have become an inevitable part of daily water consumption, highlighting the urgent need for further studies for their potential health effects.

Pathophysiological mechanisms of cardiovascular damage induced by MNPs

The pathophysiology of MPs and NPs in affecting the CVS is multifaceted, involving several complex mechanisms. Exposure to MPs and NPs can result in oxidative stress, which can lead to cellular damage and increase the susceptibility to cardiovascular disorders[33]. These particles are present in various environmental areas, including water systems, sparking considerable concern about their potential health effects on the CVS[34].

Oxidative stress and cellular damage

One critical mechanism by which MPs and NPs affect the CVS is by inducting oxidative stress. This oxidative stress arises due to the production of reactive oxygen species (ROS), which can lead to cellular injury and inflammation, playing a role in the development of cardiovascular diseases. For example, prolonged exposure to elevated levels of MPs has been associated with disrupted lipid metabolism and cardiovascular harm, underscoring the potential dangers linked to ongoing MP exposure[35]. The size and chemical characteristics of these particles significantly impact their interactions within human systems, highlighting the need for further research into their precise effects on cardiovascular health[36].

Cardiac mitochondria dysfunction

This oxidative stress-induced damage extends to cardiac mitochondria, compromising their function and promoting apoptosis. Dysregulation of pro-apoptotic and anti-apoptotic proteins further exacerbates cardiomyocyte death, contributing to myocardial injury and dysfunction[37]. Notably, preclinical studies using rats have underscored the adverse impact of MP exposure on cardiac structure and function. Exposure to polystyrene MPs elicited mitochondrial damage, elevated cardiac troponin I levels, and creatine kinase-MB, indicative of myocardial injury. Moreover, MP-induced oxidative stress has been implicated in cardiomyocyte apoptosis, fostering cardiac fibrosis by the activation of the Wnt/β-catenin pathway[38].

Cardiac fibrosis and remodeling

Chronic exposure to MPs and NPs also stimulates cardiac fibrosis, a critical aspect of adverse cardiac remodeling. Cardiomyocyte apoptosis serves as a trigger for the activation of fibroblasts into myofibroblasts, which proliferate and deposit excessive extracellular matrix (ECM) proteins, particularly collagen. The activation of signaling pathways such as Wnt/β-catenin further amplifies fibrotic remodeling by promoting fibroblast proliferation and ECM synthesis[38]. This pathological process compromises cardiac function and may ultimately lead to heart failure. The intricate interplay of oxidative stress, apoptosis, and fibrosis underscores the multifaceted nature of the cardiac damage induced by MPs and NPs, emphasizing the importance of comprehensive strategies to mitigate plastic pollution and safeguard cardiovascular health.

Microvascular toxicity

MPs and NPs exert microvascular toxicity, promoting hemolysis, thrombosis, and endothelial dysfunction. Hemolytic events induced by MP exposure compromise red blood cell integrity, exacerbating cardiovascular risk. As evidenced in animal models, thrombotic tendencies underscore the intricate interplay between MP surface modifications and thrombotic outcomes[39]. Endothelial damage induced by MP and NP interactions initiates inflammatory cascades, perturbing endothelial growth factor equilibrium and fostering inflammatory responses, thereby contributing to cardiovascular pathology. MPs and NPs can accelerate the premature ageing of blood vessels through the ROS-mediated cyclin-dependent kinase 5 (CDK5) signaling pathway. This pathway elucidates the molecular mechanisms by which MPs contribute to vascular ageing and associated cardiovascular disorders[40]. Moreover, the accumulation of MPs and NPs in the intestine can lead to gut microbiota dysbiosis, which has been linked to various illnesses, including cardiovascular diseases. This connection underscores the indirect impact of these

particles on cardiovascular health through gut microbiota alterations[41].

Thrombus formation

Thrombus formation is another significant aspect of the pathophysiology of MPs and NPs in the CVS. These particles can interact with platelets, triggering platelet adhesion, activation, and aggregation, which are crucial steps in thrombus formation[42]. The presence of MPs and NPs in the bloodstream disrupts hemostasis, promoting thrombus initiation and propagation[43]. Furthermore, the impact of MPs and NPs on endothelial function and vascular integrity is pivotal in understanding their role in thrombus formation. *In vivo* studies have shown that ultrafine particles can lead to real-time platelet aggregation and thrombus formation, highlighting the direct effects of these particles on vascular health[44].

Impacts of MNPs on cardiovascular health: insights from recent research

Recent clinical studies have provided compelling evidence regarding the toxic effects of MPs and MNPs on cardiovascular health. These investigations have detected plastic contaminants in human arterial tissues, particularly in patients with atherosclerotic plaques. The findings suggest a concerning association between the presence of these materials and increased risks of MACE, including myocardial infarction (MI) and stroke. As the body of research grows, it becomes increasingly important to understand the mechanisms by which MPs and NPs may influence cardiovascular disease progression and to check for the broader implications of plastic exposure on public health.

Sheng *et al* used pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) to examine the existence of MPs in various human artery types, encompassing those with atherosclerotic plaques, both in carotid and coronary arteries as well as aortic specimens without plaques. MPs were identified in 17 arterial samples, demonstrating a mean concentration of 118.66 ± 53.87 μg/g of tissue. Of the detected MPs, PET was the most common, followed by polyamide-66 (PA-66), polyvinyl chloride (PVC), and PE. Significantly, the levels of MPs in arteries with atherosclerotic plaques were considerably greater than those in plaque-free aortas, suggesting a potential connection between MPs and atherosclerosis in humans[45]. These findings provide a compelling evidence of the potential role of MPs in cardiovascular pathology. However, the limited sample size highlights the need to enhance representativeness by involving a larger, more diverse cohort for broader applicability. Additionally, the study's focus on specific arterial regions, such as the carotid and coronary arteries, may overlook variability in MP accumulation across different vascular areas, potentially underestimating the systemic distribution of MPs. Addressing these gaps through expanded sampling of various arterial types and locations would provide a more comprehensive understanding of the interaction between MPs and vascular systems[45].

In a separate study, Yunxiao *et al* employed laser direct infrared chemical imaging and scanning electron microscopy to investigate the detection of MPs in cardiac tissues and adjacent anatomical areas. Although not uniformly distributed, MPs of various types were identified across different tissue types. The detection of polymethyl methacrylate in certain cardiac tissues was remarkable, indicating intentional exposure during surgical procedures and offering clear evidence of MP infiltration in individuals undergoing cardiac surgery. More research is essential to examine the effects of surgical procedures on MP exposure and their possible ramifications for human health[46]. The results provide valuable insights into MP presence in cardiac tissues, but the focus on patients undergoing surgery introduces potential confounding factors. MP contamination from surgical instruments or materials may influence the results. Future studies could enhance these findings by implementing controls to distinguish surgical sources of contamination from environmental exposure, further refining our understanding of MP impacts on cardiovascular health.

In a study by Marfella *et al*, the main objective was to assess the occurrence of MNPs in atheromas and their potential relationship with MACE in human participants. The cohort consisted of 257 patients, yielding significant insights from the investigation. Significantly, the study detected NPs in atherosclerotic plaques and noted a higher occurrence of cardiovascular events, such as MI, stroke, or death, in patients with nanoplastic-contaminated atheromas compared to those without such findings. Throughout the study, they analyzed samples of arterial plaque obtained from 257 patients undergoing carotid endarterectomy, a surgical intervention aimed at plaque removal. Their analysis revealed the presence of PE MPs in approximately 60% of patients and PVC MPs in about 12% of patients[47]. PE and PVC are common forms of plastic extensively used in everyday items, ranging from beverage containers to construction materials[40].

Following the surgical procedure, patients were monitored for an average duration of 34 months. Those with MPs within their arterial plaque exhibited a significantly higher risk, approximately 4.5 times greater, of experiencing MACE, such as stroke, heart attack or mortality, compared to individuals without detectable plastic residues in their arteries. Regarding primary end-point events, which included nonfatal stroke, nonfatal MI, or all-cause mortality, occurrences were documented in 8 of 107 patients (7.5%) without any presence of MNPs, with an incidence rate of 2.2 events per 100 patient-years. In contrast, within the subset exhibiting MNPs, 30 of 150 patients (20.0%) experienced such events, corresponding to a rate of 6.1 events per 100 patient-years over the follow-up period of 33.7 ± 6.9 months. The hazard ratio for primary end-point events among patients with MNPs in plaque, relative to those without such evidence, was 4.53 (95% confidence interval [CI], 2.00 to 10.27; $P < 0.001$), underscoring a markedly elevated risk associated with the presence of MNPs[47]. While potential laboratory contamination is acknowledged in the study, future studies in controlled environments can confirm these findings. The lack of socioeconomic data is noted, and future research could incorporate this for a broader understanding. The focus on asymptomatic patients is valuable, but including a more diverse population would enhance generalizability. Exploring dietary and waterborne MPs could further clarify their role in cardiovascular health. Overall, the study demonstrates that MPs in carotid plaques are associated with higher cardiovascular risk[47].

Discussion

The emerging evidence surrounding the impact of MPs and NPs on cardiovascular health is concerning. Recent studies have

highlighted the potential relationship between plastic exposure and increased cardiovascular risks, underscoring the urgent need for further investigation into this issue. Yan *et al* examined the vascular toxicity of MPs by classifying patients into calcification (25) and non-calcification (22) groups based on thoracic aortic calcification. The findings showed that patients with vascular calcification (VC) had increased levels of total MPs, as well as PP and PS, in their feces. A positive correlation was found between the thoracic aortic calcification score and MP abundance, which is also significant. The investigation also incorporated an animal model to evaluate the influence of PSMP exposure on healthy rats and those given vitamin D3 and nicotine (VDN). Exposure to PSMP resulted in slight VC in healthy rats and intensified VC in rats treated with VDN. Mild calcification was observed in the ascending aortas and hearts of normal rats, while rats treated with VDN showed more pronounced calcification. These results demonstrated that PSMP exposure may adversely affect vascular health. The presence of mild calcification in normal rats and the increased severity in rats treated with VDN indicate that MPs could result CVS issues. This emphasizes the potential risks linked to MP exposure and highlights the need for further investigation into their effects on vascular health[48].

Rotchell *et al* vowed to identify MPs in five human saphenous vein tissue samples using μFTIR spectroscopy. Approximately 20 MP particles from five different polymer types were identified in four of the samples. The majority of the identified MPs were irregularly shaped (90%), with alkyd resin being the most prevalent, followed by polyvinyl propionate and acetate, and nylon-ethylene-vinyl acetate. The presence of MPs in vascular tissues raises significant concerns regarding their potential deleterious effects on cardiovascular health. MPs may provoke inflammatory responses, disrupt endothelial function, and contribute to VC. These findings suggest a potential link between VC and higher levels of MPs, particularly PP and PS. The correlation between the calcification score and MP levels indicates that increased exposure to these MPs may contribute to vascular damage or disease. This raises significant concerns about the effects of MP exposure on cardiovascular health and emphasizes the necessity for additional research into their toxicological effects[49].

Wang *et al* also investigated the potential relationship between MP levels and severity of the disease in thrombotic conditions. Samples of thrombus were obtained from patients undergoing thrombectomy for deep vein thrombosis, MI, or ischemic stroke (IS). Employing Py-GC/MS, MPs were identified in 80% of the samples, with PVC, PA-66, and PE recognized as the most common polymer types. Notably, greater concentrations of MPs were linked to heightened disease severity. Furthermore, D-dimer levels were significantly higher in the group with detected MPs compared to the group without detected MPs. This elevation in D-dimer, a marker commonly associated with thrombosis and fibrinolysis, suggests a potential correlation between the presence of MPs and heightened thrombotic activity. Furthermore, the study's multimodal detection approach provided both quantitative and qualitative evidence of MPs in thrombotic diseases. These findings advocate for larger-scale studies to confirm these trends and identify sources of exposure, as understanding the relationship between MPs and thrombotic diseases could inform clinical practice and public health strategies[50]. The significance of these findings is substantial and deserves considerable attention. The detection of MPs in arterial tissues may not only indicate exposure but could also play a direct role in CVS pathology. MPs and NPs with their ability to cause oxidative stress. It is known to cause cellular damage and inflammation, which are the key processes involved in the pathogenesis of cardiovascular diseases[33]. Such inflammation can disrupt normal vascular function, promoting atherosclerosis and other cardiovascular complications. Moreover, the interaction of these particles with the vascular system may facilitate thrombus formation, thereby compromising endothelial function and increasing the risk of thromboembolic events[42].

The elevated D-dimer levels observed in studies further highlight the association between MPs and heightened thrombotic activity, reinforcing the notion that MPs may exacerbate existing cardiovascular conditions[50]. The findings suggest that exposure to MPs and NPs is not limited to external environmental effects, rather, these substances may act as direct risk factors for cardiovascular diseases. As MPs and NPs accumulate within vascular tissues, they may alter the microenvironment, leading to chronic inflammation and vascular remodeling. This could have far-reaching consequences, not only for individual health but also for public health at large, as cardiovascular diseases are the major cause of death worldwide[51]. Fig. 1 provides an overview of the harmful effects of MPs and NPs on heart.

Addressing the growing issue of MP and NP pollution requires a multifaceted approach that combines policy measures, technological innovations, public awareness, and medical interventions. One of the most effective strategies for mitigating MP pollution is the implementation of robust policy measures. Policies aimed at improving stormwater runoff management, such as advanced drainage systems and green infrastructure, can significantly reduce MP influx into waterbodies. Measures such as plastic bag bans, bottle taxes, and restrictions on single-use plastics have also proven effective in reducing plastic waste at the source, which in turn reduces the likelihood of MPs entering the environment[52,53].

Another key intervention involves promoting circular economy practices, which prioritize recycling and the reduction of plastic waste through sustainable material use. Bio-based polymers and market-based instruments that encourage the use of biodegradable alternatives to conventional plastics should be used. This shift toward sustainable materials, alongside enhanced recycling efforts, can significantly reduce both plastic production and the generation of MPs. Public awareness and education are equally important in encouraging individuals to reduce their consumption of single-use plastics and support eco-friendly alternatives[54]. Increasing consumer awareness about the health risks posed by MPs and NPs can motivate individuals to adopt more sustainable practices. Public health campaigns focused on reducing plastic waste and promoting reusable or biodegradable products can foster a cultural shift toward sustainability, while community-based conservation efforts can help enhance local stewardship of environmental resources. In addition to preventive measures, there is a growing need for research into therapeutic interventions to mitigate the health impacts of MP and NP exposure. Pharmacological approaches, such as antioxidants and anti-inflammatory agents, may offer protection against the oxidative stress and inflammation induced by MPs and NPs[55]. Furthermore, continuous monitoring of air and water quality is essential to understand exposure

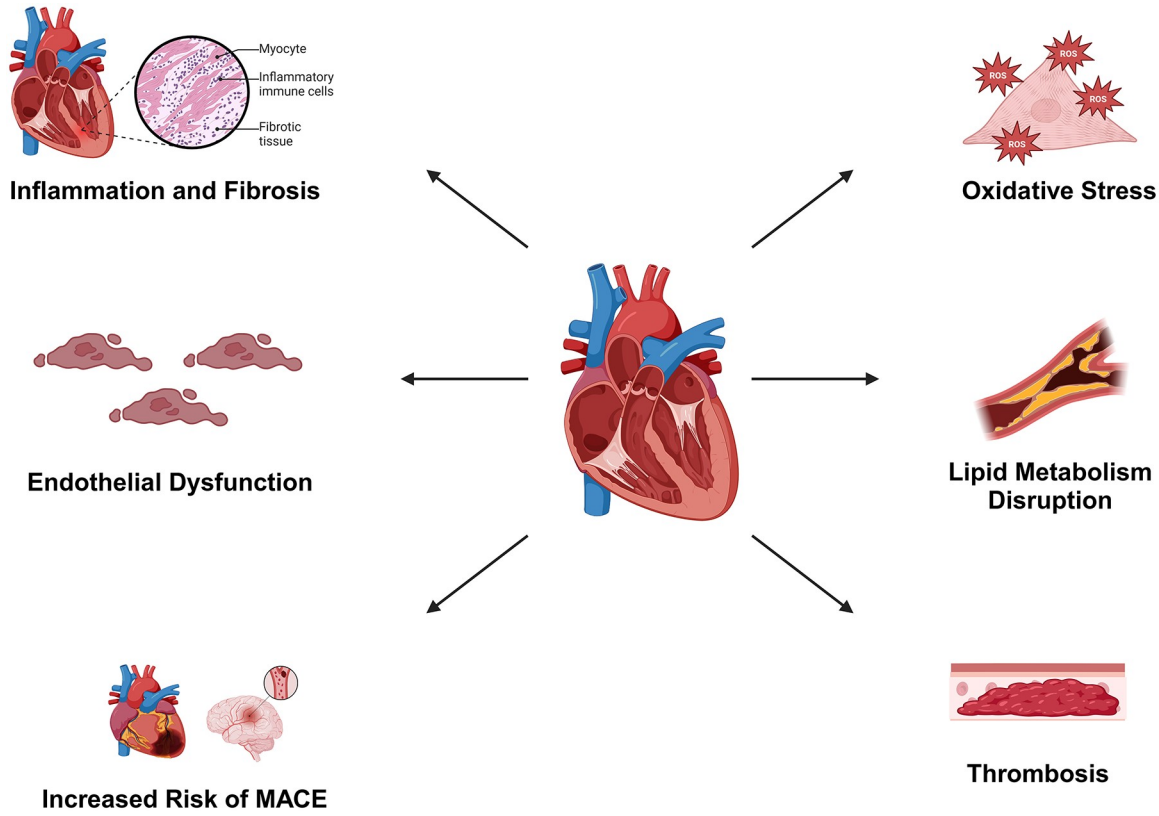

Figure 1. Adverse cardiovascular effects of microplastics and nanoplastics.

levels and guide public health responses. It is important to use advanced air filtration and monitoring systems to assess indoor air quality, which is a critical route of MP exposure. By implementing such systems, policymakers and health professionals can gather real-time data, identify exposure hotspots, and devise targeted interventions to reduce MP contamination.

Several limitations must be considered when interpreting the findings.

A notable concern is the variability in methodologies across the included studies, which may contribute to inconsistencies in findings. Differences in MPs and NPs characterization, such as particle size, shape, and concentration, may affect the detection and quantification of MPs and NPs, influencing the reliability of the reported effects. Some studies used different methods for detecting and quantifying MPs and NPs, which may hinder the comparability of results. Standardized protocols are crucial for enabling cross-study comparisons and drawing more definitive conclusions regarding the health implications of these particles. Moreover, the complexity of interactions between MPs, NPs, and biological systems complicates the task of isolating their specific effects on cardiovascular health. Factors such as the chemical composition of the particles, the route of exposure, and individual susceptibility can all influence observed health outcomes. Future studies should aim to unravel these complexities by investigating the mechanisms through which MPs and NPs exert their effects, potentially paving the way for targeted interventions. In addition, the limited sample sizes and specific populations examined in some studies, such as focusing on patients with pre-existing cardiovascular conditions or undergoing surgery may not be representative of the general population. This could introduce selection bias and limit the generalizability of findings. Larger, more diverse cohorts, as well as studies that account for variables like socioeconomic status and dietary MP exposure, would provide a broader understanding of the implications of MP and NP contamination. Finally, while some studies acknowledge potential contamination during sample collection or analysis, more rigorous control measures, such as clean-room environments and comprehensive contamination controls, would help strengthen the reliability of future research. Standardized and controlled methods will be essential to isolate the impact of MPs and NPs on cardiovascular health and better inform public health strategies.

Conclusion and future recommendations

In conclusion, the increasing production and insufficient waste management of plastics have resulted in widespread contamination of natural environments with MPs and NPs, presenting substantial risks to human health, especially regarding CVS health. Mechanistic understanding of the harmful impacts of MPs and NPs on CVS health reveals that oxidative stress, cell death, and tissue scarring are critical processes that lead to heart damage and impaired function. Moreover, microvascular toxicity induced by plastic particles exacerbates cardiovascular risk through hemolysis, thrombosis, and endothelial dysfunction. The presence of MPs within human arterial plaques, as evidenced by various studies, underscores the potential association between plastic pollution and cardiovascular diseases, including

atherosclerosis. The increased likelihood of MACE in people with arterial plaques contaminated by MPs highlights the pressing necessity for intervention measures to reduce plastic pollution and protect heart health.

Given these potential pathways, prioritizing research into the cardiovascular toxicology of MPs and NPs is essential. Comprehensive insights into exposure sources, the biological mechanisms driving these particles' harmful effects, and the outcomes of prolonged exposure are critical to formulating effective prevention and treatment strategies. With plastic pollution continuing to rise, urgent research is needed to fully assess its health risks. To address these issues, stringent regulations should be enforced to curb plastic production and usage. Strengthening waste management systems to reduce plastic entry into ecosystems is crucial, alongside promoting studies that evaluate the long-term health risks associated with MP and NP exposure. Collaborative efforts among scientists, policymakers, and stakeholders are also vital in creating well-rounded strategies to lessen the health and environmental impacts of plastic pollution.

Ethical approval

Not applicable.

Consent

Not applicable.

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Author contribution

Hamza Irfan, Haider Irfan: conception of the study, drafting of the work, final approval and agreeing to the accuracy of the work. Muhammad Ahtesham Khan, Oyku Inanc, Md. Al Hasibuzzaman: drafting of the work, final approval and agreeing to the accuracy of the work.

Conflicts of interest disclosure

All the authors declare to have no conflicts of interest relevant to this study.

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