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Microplastics and nanoplastics: Emerging threats to female reproductive health and developmental outcomes

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ABSTRACT

Microplastics (MPs) and nanoplastics (NPs) have become significant environmental contaminants with growing concern about their effects on female reproductive health. These particles, which can enter the body through ingestion, inhalation, and skin contact, have been found to accumulate in reproductive organs, causing harm. MPs/NPs are linked to oxidative stress, hormonal disruption, DNA damage, and epigenetic changes, which can negatively affect fertility, oocyte quality, and embryo development. The potential cross-generational effects of MPs/NPs could impact offspring's immune systems, neurological development, and metabolic processes, posing long-term health risks. Additionally, MPs/NPs can act as carriers for other pollutants, amplifying their toxicity when co-exposed. Although much of the research comes from animal models, the implications for human health are concerning. Addressing the risks associated with MPs/NPs requires further investigation into their mechanisms, combined with robust environmental policies and public health strategies to protect reproductive health and reduce exposure to these harmful contaminants.

KEYWORDS

Microplastics (MPs); Nanoplastics (NPs); Female reproductive health; Oxidative stress; Endocrine disruption; DNA damage; Oocyte quality; Embryo development; Cross-generational effects

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Introduction

Microplastics (MPs; <5 mm) and nanoplastics (NPs; <1 μm) have emerged as ubiquitous environmental pollutants, raising growing concern due to their presence not only in ecosystems but also within the human body [1]. These particles can enter the body through ingestion, inhalation, and skin contact, and have been detected in human blood, lungs, placenta, and most recently, ovarian follicular fluid highlighting their potential impact on female reproductive health [2]. In addition to previously documented effects on the liver, gastrointestinal system, and inflammation, increasing attention is being paid to their reproductive toxicity. MPs/NPs may disrupt hormonal balance and impair cellular function in the ovaries, leading to infertility and negative pregnancy outcomes [3]. Furthermore, they can interact with other environmental contaminants, potentially amplifying their toxic effects. Studies across species report outcomes ranging from reproductive failure to transgenerational developmental disorders. Although direct parallels to human outcomes require further investigation, these findings provide a critical framework for understanding the reproductive risks posed by micro-and nanoplastics [4].

Endocrine Interference of MPs/NPs

Microplastics (MPs) and nanoplastics (NPs) are increasingly recognized as endocrine-disrupting pollutants that may interfere with female reproductive health by altering hormonal balance and energy metabolism [5,6]. These particles often carry chemical additives like bisphenol A (BPA) and phthalates, which can mimic or block hormonal signals, disrupting processes essential for ovulation, implantation, and fetal development. Emerging evidence also suggests that MPs/NPs may impair energy allocation by affecting digestive function, a phenomenon well-documented in smaller species like zooplankton [7]. Studies indicate these particles can weaken intestinal barriers and disrupt nutrient absorption, potentially leading to metabolic stress and reduced energy availability for reproductive functions. Although most findings are based on tiny organisms where digestive obstruction by MPs/NPs is more evident there is growing concern that similar mechanisms could operate in humans [8]. While direct evidence in humans remains limited, this energy-reproduction link highlights a critical area for future research on how MPs/NPs may silently undermine fertility and developmental outcomes.

Reproductive Toxicity of MPs/NPs

Microplastics (MPs) and nanoplastics (NPs) have been increasingly identified as potential reproductive toxicants, raising significant concern over their impact on female fertility and developmental outcomes. These particles, due to their small size and chemical composition, can penetrate biological barriers and accumulate in reproductive tissues [9]. Recent studies have detected MPs/NPs in ovarian follicular fluid, suggesting direct exposure to oocytes and the surrounding hormonal microenvironment. Their presence can trigger oxidative stress, inflammation, and hormonal disruptions, all of which are critical factors in ovarian dysfunction, impaired folliculogenesis, and reduced oocyte quality [10, 11].

Animal studies across various species have demonstrated that MPs/NPs exposure leads to diminished fertility, abnormal embryonic development, and even transgenerational effects, including developmental delays and genetic damage in offspring. Moreover, MPs/NPs often serve as vectors for other environmental contaminants such as heavy metals and

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endocrine-disrupting chemicals, compounding their toxicity through synergistic interactions. While translating these findings directly to humans requires caution, the physiological mechanisms observed provide strong biological plausibility for concern [12]. The impact of MPs/NPs on reproductive health extends beyond individual fertility, potentially influencing public health outcomes through reduced birth rates and compromised offspring health. Continued research is crucial to elucidate these effects and implement preventive strategies to reduce exposure, particularly among women of reproductive age.

Genotoxicity of Microplastics and Nanoplastics (MPs/NPs)

Microplastics and nanoplastics have recently gained attention for their potential to cause genetic harm, particularly in the field of reproductive health. Due to their microscopic size, these particles can penetrate deep into tissues and cells, where they may directly interact with genetic material or provoke stress responses that lead to DNA damage [13]. In females, this raises serious concerns, as such genetic disruptions can impair egg quality, hinder embryo development, and negatively influence the health of future offspring.

Deoxyribonucleic acid (DNA) damage

Scientific studies have shown that exposure to micro- and nanoplastics can cause increased DNA damage and oxidative stress. These particles often trigger the production of reactive oxygen species (ROS), which can attack DNA, leading to strand breaks, structural chromosome abnormalities, and changes in gene activity. Such damage, particularly in reproductive cells, can affect the maturation of eggs and the development of embryos [14]. If it occurs during early stages, the genetic errors may be passed on to future generations, contributing to infertility or developmental issues.

Epigenetic effects

In addition to damaging DNA directly, micro- and nanoplastics may also bring about changes in gene regulation through epigenetic pathways. These include modifications like DNA methylation, shifts in histone structure, and disruptions in microRNA expression. Such alterations can interfere with hormone signaling, egg development, and embryo implantation. What's especially concerning is that these epigenetic changes can be inherited, meaning they might impact not only the individual exposed, but also their descendants. Animal studies suggest that exposure during sensitive reproductive periods can lead to long-term disruptions in gene expression involved in fertility and development [15].

These findings highlight the urgent need to further explore how micro- and nanoplastics affect reproductive health at the genetic level, especially for women of reproductive age.

Cross-generational Toxicity of Microplastics and Nanoplastics (MPs/NPs)

Microplastics (MPs) and nanoplastics (NPs) pose a growing threat not only to directly exposed individuals but also to their progeny, with mounting evidence suggesting their ability to disrupt physiological processes across generations. The concern surrounding transgenerational toxicity has intensified following the detection of MPs/NPs in placental tissues and follicular fluid, indicating their ability to cross critical biological barriers during gestation and early development [16]. These findings suggest that maternal exposure during pregnancy may result in persistent and heritable changes in offspring, affecting a broad range of physiological systems.

One area of particular vulnerability is the development of the immune system. MPs/NPs have been shown to interfere with immune homeostasis in exposed mothers, which may, in turn, impair the developing immune microenvironment of the fetus. Animal studies demonstrate that prenatal plastic exposure can lead to altered cytokine profiles and weakened immune responses in offspring, leaving them more susceptible to infections or inflammatory disorders. These early-life immune disturbances may persist long after birth, shaping immune resilience and disease susceptibility throughout the lifespan.

Vascular and circulatory development is another critical target of transgenerational plastic toxicity. The placenta plays a vital role in mediating nutrient and oxygen transport between mother and fetus. Disruption of placental vasculature by MPs/NPs has been linked to impaired fetal growth and reduced perfusion. Experimental data suggest that exposure to these particles can compromise endothelial function and disturb angiogenesis, leading to long-term effects on cardiovascular health in the offspring. Such disruptions may also influence fetal blood pressure regulation and organ perfusion, predisposing individuals to hypertension and other circulatory disorders later in life [17,18].

In parallel, the developing nervous system may be particularly vulnerable to MPs/NPs due to its complexity and sensitivity during early stages. Studies in rodent models have demonstrated that prenatal exposure to plastic particles can lead to neurobehavioral alterations, including anxiety-like behavior, memory deficits, and motor dysfunctions in juvenile and adult offspring. These outcomes are believed to stem from increased oxidative stress and neuroinflammation, which interfere with neural pathway development and synaptic plasticity. The potential for long-term neurodevelopmental effects raises significant concern for future human cognitive and behavioral health (Figure 1).

Moreover, metabolic processes in the offspring can also be affected, particularly regarding glucolipid regulation. Disruption of maternal metabolism by MPs/NPs may have a programming effect on the fetal metabolic axis, contributing to insulin resistance, altered lipid profiles, and an increased risk of obesity in progeny. Some studies suggest that MPs/NPs may alter gut microbiota composition or impair liver function, both of which play essential roles in metabolic regulation and energy balance. These effects could have enduring consequences that extend into adulthood [19].

Lastly, the reproductive capacity of offspring may also be jeopardized by early plastic exposure. Evidence indicates that MPs/NPs can impair the formation of reproductive organs, alter hormone levels, and disrupt the development of the hypothalamic-pituitary-gonadal (HPG) axis. Such interference may result in reduced fertility, hormonal imbalances, and even early onset of reproductive aging in exposed generations. These findings highlight the possibility of a perpetuating cycle of reproductive vulnerability.

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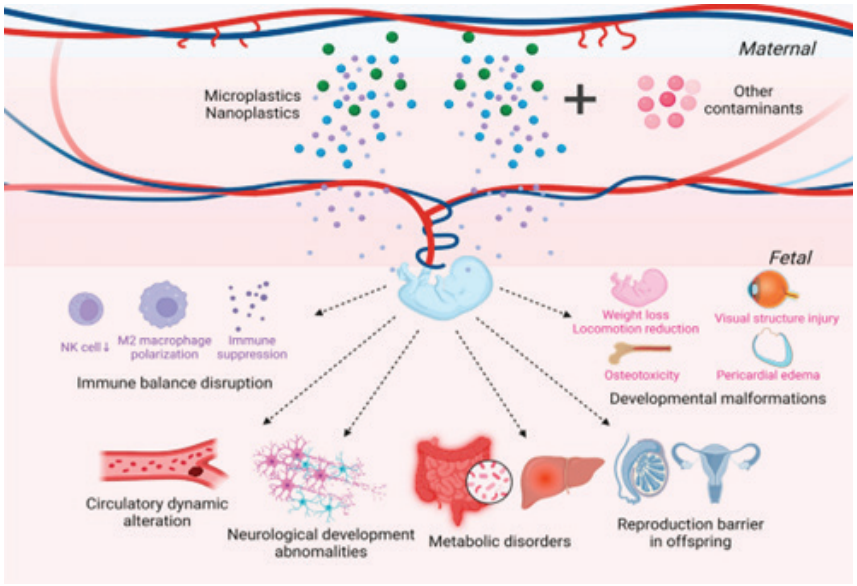

Figure 1. Cross-Generational Toxicity of Microplastics and Nanoplastics: Impact on Immune, Circulatory, Neurological, and Metabolic Health in Offspring.

Source. [Toxicity of microplastics and nanoplastics: invisible killers of female fertility and offspring health]

Combined Effects of MPs/NPs with Other Pollutants in Reproductivity

The toxic potential of microplastics (MPs) and nanoplastics (NPs) is not limited to their individual properties. These particles can act as vectors or carriers for a wide range of environmental contaminants, thereby amplifying their biological impact. When combined with other pollutants, particularly organic and inorganic toxins, MPs/NPs can result in synergistic, additive, or even antagonistic effects that significantly exacerbate reproductive toxicity [20]. This complex interplay raises serious concerns, especially regarding female reproductive health and developmental outcomes in offspring.
MPs and NPs are highly adsorptive surfaces capable of binding various organic pollutants, including persistent organic pollutants (POPs), endocrine-disrupting chemicals (EDCs), polycyclic aromatic hydrocarbons (PAHs), pesticides, and plasticizers like bisphenol A (BPA) and phthalates. These contaminants are often hydrophobic and tend to accumulate on the plastic surface during environmental exposure. Once ingested or absorbed, the combined presence of MPs/NPs and these pollutants can enhance their bioavailability and toxicity.

In the reproductive context, the presence of MPs/NPs loaded with EDCs has been linked to altered estrogen and progesterone signaling, hormonal imbalances, impaired follicular development, and irregular estrous cycles. Studies have demonstrated that co-exposure to MPs and BPA, for instance, disrupts the hypothalamic-pituitary-gonadal (HPG) axis more significantly than either pollutant alone. This disruption can reduce ovarian reserve, impact oocyte quality, and impair endometrial receptivity.

Additionally, MPs/NPs may facilitate the prolonged retention and slow release of these chemicals within reproductive tissues, leading to chronic exposure and bioaccumulation. In aquatic organisms, co-exposure has resulted in lower fertility rates, abnormal gametogenesis, and defective embryonic development—effects that may be relevant to mammalian systems as well. Importantly, since many organic pollutants mimic natural hormones, their transport by MPs/NPs poses a unique risk of long-term endocrine disruption and reproductive dysfunction [21].

The interaction of MPs/NPs with inorganic pollutants such as heavy metals (lead, cadmium, mercury, arsenic), nitrates, and other trace elements is another concerning pathway for reproductive toxicity. These metals, when bound to MPs/NPs, may exhibit increased cellular uptake due to the small size and surface characteristics of the particles, enhancing their penetration into reproductive tissues.

Heavy metals are well-documented reproductive toxicants, known to induce oxidative stress, DNA damage, apoptosis, and mitochondrial dysfunction. When coupled with MPs/NPs, the severity of these effects may increase through combined mechanisms. For instance, MPs/NPs may weaken cell membranes or disrupt tight junctions, allowing easier intracellular entry for metal ions. Once inside, they can interfere with oocyte maturation, fertilization processes, and embryonic development.

Furthermore, MPs/NPs can act as physical stressors, damaging the epithelial lining of reproductive organs and increasing the permeability of biological barriers such as the placenta and blood-ovary barrier. In this way, they may facilitate the translocation of heavy metals to sensitive sites, including the fetal compartment [22]. Evidence from rodent studies has shown that maternal exposure to MPs combined with cadmium results in higher rates of miscarriage, fetal malformations, and impaired uterine vascularization compared to exposure to cadmium alone.

Another emerging concern is the alteration of oxidative stress responses. Both MPs/NPs and metals generate reactive oxygen species (ROS), which can damage lipids, proteins, and DNA. In reproductive tissues, ROS overproduction can lead to follicular atresia, luteal insufficiency, and reduced embryo viability [23]. When combined, the oxidative burden may overwhelm antioxidant defenses, creating a hostile environment for both conception and fetal development.

Conclusions

The growing body of evidence on microplastics (MPs) and nanoplastics (NPs) underscores their potential as serious environmental and public health threats, particularly concerning female reproductive health. These particles can infiltrate the body through ingestion, inhalation, or skin contact and accumulate in reproductive tissues, where they may trigger oxidative stress, endocrine disruption, DNA damage, and

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epigenetic alterations. The reproductive toxicity of MPs/NPs has been linked to reduced fertility, poor oocyte quality, disrupted hormonal regulation, and compromised embryo development. Alarmingly, these effects may extend across generations, impacting immune responses, neurodevelopment, metabolism, and reproductive function in offspring. Furthermore, MPs/NPs can act as vectors for organic and inorganic pollutants, enhancing their bioavailability and toxic impact, and thus amplifying the risks to reproductive integrity. While much of the data stems from animal models, the parallels with human systems warrant serious concern. To mitigate these risks, comprehensive research, improved environmental policies, and public health strategies are essential. Recognizing and addressing the compound effects of MPs/NPs is critical to safeguarding reproductive health and ensuring a healthier future for generations to come.

Disclosure statement

No potential conflict of interest was reported by the authors.

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