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Nanoparticles for Biomedical Science and Research

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Authors' contributions

This work was carried out in collaboration among all authors. Author SB wrote the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Nanoparticles refer to clusters of a few to several thousand atoms or molecules. The term "nano" refers to their size, typically ranging from 1 to 100 nanometers; a nanometer (symbol: nm) is equal to 10^{-9} meters = 0.000 000 001 meters = 1 billionth of a meter = 1 millionth of a millimeter. According to ISO/TS 27687:2008, nanoparticles are nano-objects with three outer dimensions. "Nano" is derived from the Greek "nanos" meaning "dwarf" or "dwarfish." Nanoparticles can be composed of various substances and pose an environmental burden. Nanoparticles made of plastic, smaller than microplastics, are called nanoplastics.

There are numerous potential applications for nanoparticles. They could be used to enhance various household materials. In medicine, nanoparticles could facilitate targeted drug delivery in the body or provide a gentler form of cancer therapy. Additionally, in electronics, nanoparticles could contribute to enabling more powerful and smaller computers. The significant benefits of nanoparticles have led to a drastic increase in their production and application, but it also presents

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a wide range of potential hazards for us and our environment. It is still unclear which nanoparticles have an impact on organisms. Ecotoxicology addresses potential hazards posed by nanoparticles during their production, use, and disposal, as nanoparticles exhibit novel chemical and physical properties.

Keywords: Nanoparticle; medicine; ecotoxicology; nanoplastics.

1. INTRODUCTION

The terms nanoparticle or nanoparticle refer to aggregates of a few to several thousand atoms or molecules. The name Nano refers to their size, which typically ranges from 1 to 100 nanometers; One nanometer (symbol: nm) is equal to 10^-9 m = 0.000 000 001 meters = 1 billionth of a meter = 1 millionth of a millimeter. Nanoparticles are defined as nano-objects with three outer dimensions according to ISO/TS 27687:2008. "Nano" is derived from the Greek "nanos" for "dwarf" or "dwarfish". Nanoparticles can be made of different substances and pose an environmental burden. Nanoparticles made of plastic that are smaller than microplastics are called nanoplastics. There are many potential applications for nanoparticles (Dağlıoğlu, 2025a). For example, they could be used to improve various household materials. In medicine, nanoparticles could be used to achieve targeted drug delivery in the body or a gentler form of cancer therapy (Lewinski et al., 2008). In electronics, nanoparticles could contribute to enabling more powerful and smaller computers (Eilers et al., 2020). The high potential for benefits has led to a drastic increase in the production and use of various types of nanoparticles, but it also opens up a wide range of potential dangers for us and our environment (Dağlıoğlu & Özkan Yılmaz, 2025). It is still unclear which nanoparticles have an effect on organisms. Ecotoxicology deals with possible hazards posed by nanoparticles during their production, use, and disposal, as nanoparticles exhibit novel chemical and physical properties (Richards et al., 2024).

Properties of nanoscale particles: Ultimately, these properties of nanoparticles are based on the extremely high surface charge seeking compensation. However, this increased reactivity limits the lifespan as "singular nanoparticles" to very short times. If targeted isolation through ion or micelle loading does not occur, charge balance occurs very quickly through agglomeration or aggregation, which can only be resolved again with correspondingly high energy inputs according to the 2nd law of thermodynamics. The lifespan of singular nanoparticles can be a criterion in risk assessment and occasionally exclude the inclusion of nanostructured materials in risk assessments (Dağlıoğlu et al., 2025a). Nanoparticles exhibit special chemical and physical properties that significantly differ from those of bulk solids or larger particles. These include higher chemical reactivity due to large specific surface area (large particle surface area relative to volume), reduced influence of mass forces and increasing influence of surface forces, increasing importance of surface charge and thermodynamic effects (Brownian molecular motion), resulting in stable suspensions or aggregation and special optical properties (Najahi-Missaoui W et al. 2020). These nanoparticle properties are based on the extremely high surface charge seeking compensation. However, this increased reactivity limits the lifespan of "singular nanoparticles" to very short periods (Hendricks AR et al. 2023). Without targeted isolation through ion or micelle loading, charge balance occurs quickly through agglomeration or aggregation (e.g., through ultrasonic treatment and vortexing), which can only be resolved with correspondingly high energy inputs, according to the second law of thermodynamics (Ali M et al. 2023, XU M et al. 2024). The lifespan of singular nanoparticles can be a criterion in risk assessment and occasionally exclude the inclusion of nanostructured materials in risk assessments (Madadi M et al. 2023; Dağlıoğlu & Öztürk, 2025a).

Occurrences and Forms of Nanoparticles: Nanoparticles can enter the environment through natural means (e.g., viruses, volcanic eruptions, or anthropogenic influences, such as vehicle and industrial emissions (Jaison JP et al. 2024; Dağlıoğlu & Türkis, 2025). Industrial soot refers to very small carbon particles that can be generated during combustion processes. Synthetic nanoparticles are artificially produced particles with new properties and/or functionalities, such as electrical conductivity and chemical reactivity (He Q et asl. 2020). Synthetic nanoparticles can be classified based on their chemical and physical properties (Medina C et al. 2007). Commonly used groups in research and applications include: metal and semiconductor oxides (silicon dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), iron oxides (Fe_2O_3 or Fe_3O_4), zinc oxide (ZnO), as well as zeolites and other silicon-based mesoporous materials like MCM-41 or SBA-15), semiconductors (cadmium telluride (CdTe), cadmium selenide (CdSe), silicon), metals (gold (Au), silver (Ag), iron (Fe)), metal sulfides and nanoplastics (Wen J et al. 2021). Carbon-containing nanoparticles can exist in various forms like Fullerenes, single- and multi-walled nanotubes, Graphene, Nanofibers, Polymers such as dendrimers and block copolymers, industrial soot, diamond-like and onion-like carbon (Zaman M et al. 2014). Industrial soot is composed of 96–99% carbon, with the remaining portions being hydrogen, oxygen, nitrogen, and sulfur, mostly chemically bound to the surface (Dağlıoğlu & Öztürk, 2021). The oxidized groups on the pore surface have the greatest influence on the physicochemical properties of industrial soot, such as water adsorption capacity and catalytic, chemical, and electrical reactivity (Cui G et al. 2022). Mainly, basic hydroxy, acidic carboxy, as well as carbonyl and lactone groups form on the surface. During the production of active soots, functional oxygen groups with a mass fraction of up to 15% can be introduced (Mohanto S et al. 2024).

"Ultrafine Particles": Ultrafine particles are particles with a thermodynamic diameter of less than 0.1 µm, regardless of their specific characteristics, in air quality measurements (Jaque D et al. 2014). The thermodynamic diameter describes a spherical particle with identical diffusion behavior to the particle under consideration.

Semiconductor Nanoparticles: Semiconductor nanoparticles exhibit special fluorescence properties (Chugh G et al. 2022). Similar to macroscopic semiconductors, they have a band gap, meaning that optical excitation can generate excitons (electron-hole pairs) that emit photons upon recombination, i.e., emit light in the form of fluorescence (Arick DQ et al. 2015). The energy of the photons correlates with the particle size, with the band gap increasing as the particle size decreases.

Carbon Nanotubes: Carbon nanotubes consist of cylindrical graphite layers with diameters of 1–100 nm (Kim et al. 2024). They exhibit high thermal conductivity, high tensile strength, extreme elasticity, and durability (Talkar S et al. 2018, Amreddy N et al. 2017). Depending on the structure, the electrical properties within the tube can be conductive or semiconductive.

Metals: Metallic nanoparticles have altered chemical properties compared to larger configurations of metals due to their smaller size and resulting high surface-to-volume ratio. (Feliu N et al. 2014). For example, colloidal gold exhibits stronger catalytic activity and significantly lower melting points at very small sizes. Gold, copper, silver, and other metal nanoparticles show different optical properties compared to the same metals in larger arrangements, with a broad absorption band in the visible spectrum and intense color (characteristic color of gold colloids: red to purple) (Ali M et al. 2023, Jergens E et al. 2023, Medina C et al.2007).

Nanowater: Researchers in the United States successfully created stable nanowater droplets with a diameter of 25 nanometers using electrospray. These nanowater droplets remained stable for up to four hours due to increased surface tension compared to normal water droplets. Additionally, highly reactive oxygen radicals like hydroxyl radicals and superoxides were encapsulated in the nanodroplets, which exhibited aggressive behavior by damaging the cell membranes of airborne bacteria, leading to the term "nanobomb" for the water particles. Nanowater was considered for use as a residue-free disinfectant.

Distinction from Aerosols: Aerosol is the collective term for finely dispersed solid and liquid particles (particulates) of different sizes suspended in gases (Wang S et al. 2024, Guan K et al. 2023). The same natural laws apply to nanoparticles suspended in gas, regardless of whether they are intentionally or unintentionally generated.

Production: Various methods have been established for producing nanoparticles, categorized as Bottom-Up and Top-Down approaches, depending on whether a material is nanostructured (Top-Down) or particles are synthesized from a fluid phase.

Top-Down Methods:

- Grinding processes
- Laser ablation

- Lithographic methods such as:
- Photolithography
- Electron-beam lithography
- Nano-imprint lithography

Bottom-Up Methods:

- Chemical synthesis in solutions (e.g., sol-gel method)
- Plasma synthesis using gaseous reactants, alternatively through a heated reactor (e.g., chemical vapor deposition)
- Self-organized diffusion-limited growth on surfaces or with templates (e.g., hydrothermal synthesis of nanoporous cetineites)
- Targeted nucleation of molecules from a supersaturated liquid or gas phase (Ostwald ripening or precipitation)
- Electrospinning
- Microemulsion techniques
- Solvated metal atom dispersion (SMAD)

The choice of nanoparticle production method depends on the desired particle size distribution and the chemical nature of the nanoparticles (Starsich et al. 2019). Processes in solution or self-organization typically yield the best results, but they are challenging to scale up for industrial production.

2. APPLICATIONS

Nanoelectronics: Carbon nanotubes and semiconductor nanowires have been used to create logic circuits, potentially leading to the realization of nanocomputers (Zhang X et al.2019). Zinc oxide nanoparticles have also been demonstrated in logic circuits. Due to their transparency to electromagnetic waves in the visible spectrum, these circuits are particularly interesting for transparent electronics. Zinc oxide can also be deposited in nanoparticle form using printing processes, enabling circuit integration through printing. However, the performance is limited by the relatively low charge carrier mobility, making the components mainly suitable for low-cost/low-performance applications.

Nanomaterials: Nanoparticles are already used in the production of many products (Prajitha N et al. 2019). Concrete, for example, contains nanoscale crystals that contribute to its strength. Various cosmetic products, such as sunscreens, deodorants, and toothpaste, contain nanoparticles like titanium dioxide (TiO2) and aluminum oxide (Al2O3). Nanoparticles are also added to food products. Nanocomposites are being researched for more efficient lithium-ion battery electrodes at the Nano Energy Technology Center (NETZ). Further examples include nanoparticles in paints, coatings, and surface treatments for protection against mechanical damage. Nanoparticles are also used in modern tires to reduce rolling resistance and save fuel (Khan FA et al. 2018). Additionally, nanoporous filters are being developed for improved exhaust gas cleaning in vehicles.

Disposal: There is limited experience and knowledge regarding the disposal of nanoparticles (Chen X et al. 2022). Initial studies on nanoparticle combustion showed that they mostly remain in the ash and slag during synthesis. Further research is ongoing to understand the fate of nanoparticles in water and sewage sludge (Deng H et al. 2018).

Potential Risks: The reactivity and widespread use of nanoparticles pose a broad spectrum of potential risks for human health and the environment (Sampath S et al. 2024, Daglioglu Y et al. 2018, Öztürk B et al. 2021). Studies on ecotoxicology of nanoplastics suggest that they can enter the food chain, reaching humans and animals and causing health issues (Singh D et al. 2014, Heath JR et al. 2015). Nanoplastics have been shown to damage the cell membranes of living organisms (Daglioglu Y et al. 2018, Öztürk B et al. 2021). Therefore, it is essential to assess the potential harmful nanoparticles during their production processes, especially when the direct benefits are limited. The German Federal Environment Agency recommends avoiding products with nanoparticles until their effects on the environment and human health are better understood. Studies have shown that nanoparticles can affect brain development in fetuses and lead to lung inflammation in animal models. Numerous studies highlight the potential environmental and health risks of nanotechnologies, such as nanoparticle uptake through the respiratory system, skin, and oral ingestion. The use of nanoparticle-containing products can expose individuals to potentially harmful substances, leading to health issues. It is crucial to establish standardized methods for nanoparticle characterization and measurement to assess their safety accurately.

3. CONCLUSION

Overall, the risks associated with nanoparticles in terms of human health and the environment are still being actively researched, and caution is advised in their production, use, and disposal.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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