



Silica Nanoparticles: Unlocking New Possibilities for Soil and Water Remediation

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ABSTRACT

The accelerating pace of industrialization and urbanization has led to profound environmental degradation, marked by the widespread contamination of soil and water resources with heavy metals, organic pollutants, and pathogenic microorganisms. These pollutants pose serious public health risks, contributing to millions of premature deaths globally through cardiovascular diseases, respiratory disorders, and waterborne diseases. While conventional remediation methods (physical, chemical, and biological) have contributed significantly to pollution control, they are often hindered by high operational costs, limited efficiency, and the generation of hazardous byproducts. Nano-remediation has emerged as a cutting-edge solution, offering superior efficiency through the use of highly reactive nanoparticles. Among these, silica nanoparticles (SiO₂ NPs) offer notable advantages due to their environmental compatibility, ease of functionalization, and capacity to support multiple remediation pathways. Their ability to facilitate adsorption, catalytic degradation, photocatalysis, and pollutant immobilization positions them as a versatile platform for soil and water cleanup. Continued advances in synthesis, modification strategies, and safety assessment are essential to maximize their performance while minimizing environmental risks. This review synthesizes current applications of SiO₂ NPs in remediating diverse contaminants, critically compares their performance with other nanomaterials, and highlights existing challenges, ecological considerations, and knowledge gaps requiring further investigation to guide their sustainable use in environmental remediation.

Keywords: Nano-remediation; Silica nanoparticles; Environmental pollution.

1. INTRODUCTION

The accelerating pace of industrialization and urbanization has led to widespread environmental degradation, with soil and water increasingly contaminated by heavy metals, organic pollutants, and pathogenic microorganisms. Such contamination poses significant global health and ecological risks, contributing to gastrointestinal diseases, heavy-metal toxicity, and long-term ecosystem disruption (Lin *et al.* 2022; Sharafi and Salehi, 2025).

To address these growing challenges, a range of remediation strategies has been developed, each differing in mechanism and applicability. Physical methods (such as sedimentation, filtration, and adsorption) are commonly applied for soil and water cleanup (Ugrina and Jurić, 2023), but they are often limited in their ability to remove dissolved or fine-scale contaminants. Chemical approaches, such as coagulation, oxidation, and advanced oxidation processes (AOPs), can transform or degrade pollutants (Giwa *et al.* 2021; Zhang *et al.* 2024), yet may generate harmful by-products or require substantial energy input. Biological methods, including bioremediation and phytoremediation, use microorganisms and plants to break down contaminants,

although their efficiency is strongly dependent on environmental conditions and biological activity, leading to slow and inconsistent outcomes (Yadav and Sharma, 2023).

Collectively, these limitations underscore a critical need for remediation strategies that couple efficiency with environmental compatibility. Advances in nanotechnology offer such potential, providing materials with high reactivity, engineered surface properties, and enhanced interactions with contaminants. Within this technological landscape, nano-remediation has gained particular prominence as a promising approach for addressing complex and persistent soil and water pollutants, as it employs reactive nanoparticles (NPs) for *in situ* contaminant removal while offering enhanced reactivity, minimal ecological disruption, lower toxicity, and faster remediation (Alazaiza *et al.* 2021; Swain and Das, 2025). A wide range of NPs has been explored for this purpose, including zero-valent iron (nZVI) for reducing nitrates and heavy metals (Li *et al.* 2021), TiO₂ under UV irradiation for generating reactive oxygen species (Sharma *et al.* 2022), and carbon-based materials such as graphene oxide (GO) and carbon nanotubes (CNTs) for adsorbing diverse contaminants (Madima *et al.* 2020). Other nanoparticles, including

ZnO, Fe₃O₄, γ -Fe₂O₃, and CeO₂ have also demonstrated strong remediation potential (Venkateshaiah *et al.* 2022).

Given the extensive array of nanomaterials investigated for environmental remediation, their effectiveness can vary significantly depending on properties such as stability, reactivity, environmental compatibility, and functional tunability. These variations underscore the need to identify nanoparticle platforms that combine high efficiency with predictable performance across diverse environmental conditions. Within this broader context, silica nanoparticles (SiO₂ NPs) have emerged as a particularly advantageous class of nanomaterials, owing to their distinctive physicochemical characteristics (Fig. 1). SiO₂ NPs are distinguished by their high surface area, chemical inertness, low toxicity, and exceptional capacity for surface functionalization, features that make them ideal for targeted contaminant removal (Guerra *et al.* 2018; Elizondo *et al.* 2024). Their economic viability, enhanced water mobility, and strong adsorption capacity further reinforce their versatility and effectiveness in soil and water remediation applications (Chircov *et al.* 2020; Nayl *et al.* 2022).



Fig. 1: Applications of silica-based nanoparticles

This review examines the distinctive physical and chemical properties of SiO₂ NPs and highlights the core mechanisms of action, such as adsorption, catalytic degradation, photocatalysis, and redox reactions, that drive their role in environmental remediation. The review further investigates their practical applications in soil and water cleanup and also takes into account the existing challenges and limitations and safety issues associated with SiO₂ NPs, especially in comparison to other nanomaterials.

2. PROPERTIES OF SiO₂ NPs

SiO₂ NPs, generally ranging from 1 to 100 nm in size, are composed of a silica core that includes silicon

and oxygen atoms. SiO₂ NPs are primarily recognized for their compatibility with biological systems, low toxicity, cost-effectiveness, and ease of surface modification. They exhibit a spherical and uniform structure, and their size, shape, porosity, and crystallinity can be customized to meet specific needs. Their modifiable characteristics render them ideal for a variety of uses, including catalysis, filtration, electronics, textiles, paints, and beyond (Bhat *et al.* 2021; Jun, 2021).

2.1 High Surface Area and Porosity

A key property of SiO₂ NPs is their exceptionally high surface area and porosity, which arise from their nanoscale dimensions and ability to form porous frameworks (Yu *et al.* 2012; Vallet *et al.* 2022).

Their surface area often exceeds 500 m²/g due to their small size and the abundance of surface silanol groups (Si–OH). This large surface area enables strong interactions with surrounding molecules, making them ideal for applications such as drug delivery, adsorption, and catalysis. The porous structure of SiO₂ NPs can be tailored to achieve a variety of pore sizes, generally within the mesoporous range (2–50 nm in diameter). The arrangement of these pores can be either ordered or disordered, depending upon the synthesis method employed. This porosity significantly enhances the storage capacity for small molecules, proteins, and enzymes, making SiO₂ NPs particularly advantageous in catalysis, where they can serve as supports for catalysts or be utilized in filtration processes. High surface area and porosity of SiO₂ NPs enhance their adsorption capacity, making them highly effective in capturing pollutants. These properties facilitate rapid and efficient contaminant removal in environmental remediation applications. (El-Shafey *et al.* 2024) recently reported that the newly synthesized silica/Klucel nanocomposite may achieve 95% lead removal within 60 minutes, due to its large surface area and porous nature. In addition, the material exhibited a notable adsorption capacity ($q_m = 63.938$ mg/g), followed pseudo-second-order kinetics, and maintained 65% efficiency after seven reuse cycles.

2.2 Biocompatibility

Silica nanoparticles (SiO₂ NPs) demonstrate exceptional biocompatibility and low intrinsic toxicity, characteristics that contribute to their expanding use in environmental applications, including soil and water remediation. Numerous studies have shown that SiO₂ NPs in the 20–100 nm size range do not elicit significant cytotoxic or inflammatory responses (Dong *et al.* 2020; Nicolae *et al.* 2024), and their behaviour in natural systems is influenced by factors such as particle size, surface charge, and surface coatings. Owing to their chemically inert nature, SiO₂ NPs exhibit lower toxicity than metal- or semiconductor-based nanoparticles and exert minimal disruption on soil microbial communities,

which are vital for biodegradation and nutrient cycling. This biocompatibility enables SiO₂ NPs to operate synergistically with microbial and plant-based remediation processes, enhancing pollutant degradation while preserving ecological balance (Singh *et al.* 2025). Additionally, SiO₂ NPs gradually transform into orthosilicic acid, a naturally occurring and environmentally benign compound, reducing the risk of long-term accumulation in terrestrial or aquatic systems. Their low ecological toxicity permits the use of higher nanoparticle concentrations when required for efficient adsorption of heavy metals or organic contaminants, while their stable, non-toxic core supports safe functionalization, including amine, thiol, or carboxyl groups to improve targeted pollutant capture without introducing additional hazards. Collectively, the favourable biocompatibility and environmentally benign behaviour of SiO₂ NPs underscore their strong potential as safe and effective nanomaterials for soil and water remediation.

2.3 Surface Chemistry Modification Potential

Another significant characteristic of SiO₂ NPs is their highly tailorable surface chemistry, which underpins their versatility in environmental remediation. The abundant surface silanol (Si–OH) groups provide reactive sites for covalent attachment of organic ligands, polymers, and inorganic moieties, enabling precise control over surface charge, hydrophobicity, and binding affinity. Moreover, the mesoporous architecture of SiO₂ NPs increases accessible surface area and facilitates rapid diffusion of pollutants into the pore channels, directly enhancing adsorption-driven removal in water and soil environments. By introducing functional groups such as amines (–NH₂), carboxyls (–COOH), thiols (–SH), and phosphonate or ionic-liquid moieties, the adsorption selectivity and capacity of SiO₂ NPs toward specific contaminants can be markedly enhanced. Organically functionalized mesoporous silica has been widely reported as a highly efficient adsorbent for heavy metals due to the combination of ordered porosity, large surface area, and accessible chelating groups (Da'na, 2017; Lian *et al.* 2021). Thiol-functionalized nano-silica (SiO₂–SH), for example, effectively immobilizes Pb, Cd, Cu, and other cations in contaminated soils and aqueous media, reducing plant uptake and bioavailability (Li *et al.* 2021). Likewise, amino- and carboxyl-functionalized mesoporous silicas exhibit strong binding toward dyes and pharmaceuticals, offering high removal efficiencies and good regenerability for wastewater treatment (Wang *et al.* 2024; Gou *et al.* 2021).

Surface modification also facilitates the preparation of hybrid nanocomposites, such as magnetic Fe₃O₄@SiO₂ or ZnO–silica systems, in which the silica shell provides stability and tunable chemistry, while the core contributes catalytic or magnetic properties. These

composites allow efficient adsorption or degradation of organic pollutants and heavy metals, followed by rapid recovery using an external magnetic field (Mahmoud *et al.* 2021). In water remediation, such functionalized SiO₂-based adsorbents routinely achieve high capacities for metals like Ni²⁺, Cu²⁺, Cr³⁺, and Pb²⁺, as well as for anionic and cationic dyes (Nguyen *et al.* 2019; Zhang *et al.* 2024). Similarly, in soil systems, nano-silica and its thiolated derivatives stabilize heavy metals by shifting them into less labile fractions and improving soil physicochemical properties (Zhang *et al.* 2024). Overall, the tunable surface chemistry of SiO₂ NPs provides a direct functional link between their molecular-scale design and their macroscopic performance in soil and water remediation, enabling targeted, high-capacity removal of priority contaminants.

Together, the physicochemical properties, including high surface area, tunable porosity, biocompatibility, and versatile surface functionalization, form the basis for the remediation pathways, enabling SiO₂ NPs to act as efficient adsorbents, catalytic supports, and recovery-friendly nanomaterials in contaminated soil and water systems.

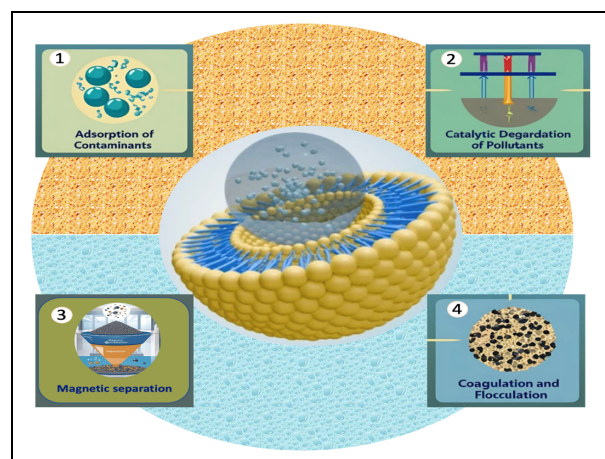


Fig. 2: Silica nanoparticle mechanisms for soil and water remediation

3. POSSIBLE MECHANISMS OF REMEDIATION BY SiO₂ NPs

SiO₂ NPs are gaining attention in soil and water remediation due to their unique properties, such as high surface area, stability, and modifiability. These nanoparticles aid in pollutant removal through adsorption, catalysis, and carrier functions for other agents (Fig. 2). Several important mechanisms, such as adsorption of contaminants, catalytic degradation of pollutants, magnetic separation when functionalized with magnetic components (magnetic SiO₂ NPs), and coagulation–flocculation-based removal strategies, provide a broad understanding of the remediation potential of SiO₂ NPs.

3.1 Adsorption of Contaminants

Adsorption involves transferring pollutants (adsorbates) from liquid to solid (adsorbents) surfaces via physical or chemical forces (Faust and Aly, 2018). Key influencing factors include pH, concentration, contact time, and adsorbent type (Jal *et al.* 2004; Ha *et al.* 2020; Moghaddam *et al.* 2020; Zeb *et al.* 2020). Siliceous materials like zeolites, alunite, perlite, and silica beads are favored due to cost and availability. Surfactant-templated silicas (e.g., CTMAB, P123, F127) are commonly used (Zeb *et al.* 2020). Silica beads possess reactive silanol groups, which act as active sites for adsorption and can be effectively used for dye removal from polluted water (Fu *et al.* 2011; Wadhawan *et al.* 2020). Alunite, a jarosite group mineral, offers higher capacity than activated carbons (Crini and Morcellet, 2002; Liberman *et al.*, 2014). Perlite, with >70% silica content, has been used for dye removal (Doğan and Alkan, 2003). Zeolites, with high ion-exchange and surface area, remove heavy metals and phenols (Doan *et al.* 2004). Diatomite, derived from diatoms, effectively absorbs acids and organics (Dill, 2001; Al-Ghouthi *et al.*, 2003; Osornio *et al.*, 2016). The method is cost-effective and widely used for removing various pollutants.

The porous SiO₂ (mesoporous silica) matrix functions as an efficient support that not only prevents nanoparticle aggregation but also enhances light utilization and accelerates pollutant transport during photocatalytic remediation. In TiO₂/SiO₂ hybrid systems, anatase nanoparticles are chemically anchored to the silica framework through Si–O–Ti linkages, which inhibit sintering and particle agglomeration under operating conditions, thereby preserving a high dispersion of active catalytic surfaces (Cruz-Quesada *et al.* 2025). The silanol-rich surface of mesoporous silica further provides strong interaction sites that stabilize embedded nanoparticles and maintain structural integrity during repeated reaction cycles. The ordered porous architecture also improves photon management within the catalyst; silica's light-scattering and transparency characteristics allow deeper light penetration, enabling more TiO₂ particles, both at the surface and within internal pores, to participate in photocatalysis (Singh *et al.* 2020). Additionally, the interconnected channel network of mesoporous silica promotes rapid diffusion of pollutants, ensuring that contaminant molecules can readily enter the pore system and reach active catalytic sites, thereby reducing mass-transfer resistance and improving degradation efficiency (Cervantes and Ramírez-Montoya, 2022). These collective advantages—aggregation control, enhanced light harvesting, and improved accessibility of pollutants—explain why mesoporous silica has become a preferred support for heterogeneous photocatalysts in environmental remediation applications.

3.2 Catalytic Degradation of Pollutants

Dyes used in various industries contribute to organic water pollution. Around 15% of dyes become wastewater, posing health risks. While several conventional methods exist, nanomaterials like silica offer high chemical stability, thermal resistance, and affordability (Biradar *et al.* 2021). Compared to other metal oxides, silica has superior photocatalytic efficiency. Variants like silica-alumina, silica-supported zirconia, magnesia, and titania perform effectively under UV light. In AOPs, SiO₂ NPs maintain structural integrity and prevent particle aggregation. Pollutants like dichlorobenzene (DCB) are degraded using AOPs involving UV, ozone, ultrasound, and hydrogen peroxide (Heponiemi *et al.* 2021). Metal oxide catalysts such as TiO₂ enhance the efficiency of these processes (Kalidhasan and Lee, 2022).

3.3 Magnetic Separation (Magnetic SiO₂ NPs)

Magnetic nanoparticle (MNP) separation is widely applied in water purification and biochemical processes due to its ability to quickly recover catalytic or adsorptive particles using an external magnetic field (Iranmanesh and Hulliger, 2017). Magnetite (Fe₃O₄) is commonly used because of its low toxicity and biocompatibility, and under a magnetic field, these particles aggregate, allowing efficient removal of bound contaminants from water (Tang *et al.* 2020). However, uncoated magnetite nanoparticles tend to oxidize, dissolve, or agglomerate, which reduces their adsorption activity and long-term stability. The application of a silica (SiO₂) coating addresses these limitations by forming a protective and chemically inert shell that prevents oxidation and particle–particle fusion while improving dispersion in water (Sharafi *et al.* 2018).

Additionally, the silica surface contains abundant silanol (–Si–OH) groups, which enhance surface functionalization and allow the attachment of chelating groups, dyes, polymers, or catalytic sites that increase affinity toward heavy metals, dyes, or organic pollutants. This improves adsorption capacity and broadens applicability in remediation systems. The resulting silica-coated magnetic nanoparticles also maintain magnetic responsiveness, enabling rapid and repeated recovery from water without loss of performance. The Stöber sol–gel method remains one of the simplest and most reliable synthesis routes for producing such silica-coated MNPs, offering controlled shell thickness and improved thermal and chemical stability (Mamun *et al.* 2021). Overall, the SiO₂ coating enhances environmental remediation by improving the chemical stability, dispersibility, reusability, and functionalization potential of magnetic nanoparticles while retaining their magnetic recoverability.

3.4 Coagulation and Flocculation

Coagulation and flocculation are essential water treatment processes in which coagulants destabilize suspended particles, forming micro- and macro-flocs that can be subsequently removed by sedimentation or flotation. Polymer flocculants may further enhance floc bonding, increasing floc size and improving settling rates. In oil–water treatment, coagulants neutralize the negative surface charge of oil droplets, promoting droplet aggregation and improving separation efficiency (Wei *et al.* 2018). While conventional coagulants such as aluminum or iron salts are widely used, silica nanoparticles (SiO₂ NPs) have gained attention as effective coagulant aids due to their ability to improve floc structure and pollutant removal performance.

For example, SiO₂ NPs added to natural organic matter (NOM)–rich water significantly improve floc compactness during coagulation with polyaluminum chloride (PAC), producing denser flocs with higher fractal dimensions and enhancing NOM removal (Xue *et al.* 2016). In wastewater containing colloidal silica, coagulation has also been shown to efficiently remove silica nanoparticles by precipitation and surface charge adsorption, demonstrating that SiO₂ can both participate in and be effectively captured by the coagulation process (Chuang *et al.* 2007). In oily wastewater systems, hybrid flocculants based on cationic polyacrylamide modified with hydrophobic nano-silica improve particle bridging and create more stable floc structures, resulting in much higher oil–water separation efficiency and lower residual turbidity (Altaf *et al.* 2025). The silanol-rich and partially hydrophobic surfaces of SiO₂ NPs enhance their interaction with suspended contaminants, improving particle adhesion, floc strength, and settling behavior.

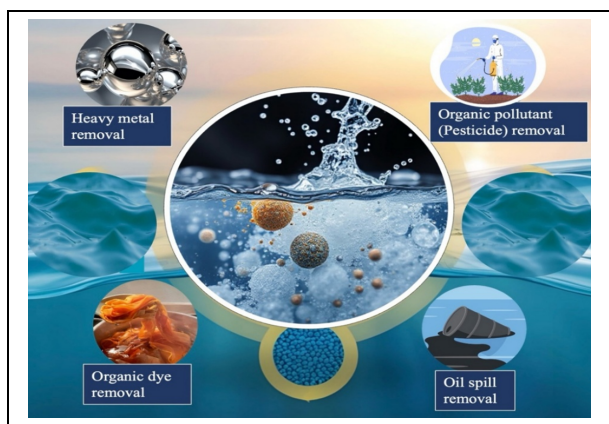


Fig. 3: Application of silica nanoparticles for water remediation

Thus, the incorporation of SiO₂ nanoparticles improves coagulation–flocculation by enhancing structural stability, bridging between particles, and strengthening pollutant capture, leading to higher

removal efficiency and better environmental remediation outcomes.

4. APPLICATIONS OF SILICA NANOPARTICLES IN WATER REMEDIATION

Since SiO₂ NPs can remove a variety of environmental contaminants, they provide a flexible and effective method for water remediation. Because of their remarkable properties, these NPs are especially good at eliminating heavy metals, organic pollutants, toxic dye colors, and oil spills from contaminated water (Fig. 3; Table 1). Their capacity to interact, catalyze, and absorb several types of pollutants makes them a viable way to improve water quality and safeguard ecosystems.

4.1 Heavy Metal Removal

Heavy metal contamination is a major global problem due to its persistence. These pollutants can enter water bodies directly or indirectly and cause toxicity or cancer. According to (Sarker *et al.* 2023), heavy metals are among the leading causes of pollution in natural water systems, posing increasing concern over environmental contamination. Major sources include sewage, industrial effluent discharges (fertilizers, steel, dyes, batteries, mining, textiles, leather, alloying, electroplating, tannery, paper, food, and cosmetics), and surface runoff. Due to their high toxicity, carcinogenicity, and bio-recalcitrance, heavy metals can penetrate the food chain and harm human health (Anjum *et al.* 2023). Studies on their removal have increased significantly from 2008 to 2018, reflecting rising global attention. Common heavy metals of concern include lead (Pb), zinc (Zn), mercury (Hg), nickel (Ni), cadmium (Cd), copper (Cu), chromium (Cr), and arsenic (As) (Qasem *et al.* 2021).

SiO₂ NPs provide a large surface area that supports adsorption (Shrestha *et al.* 2023). Their development has advanced from simple high-surface-area adsorbents to engineered functional systems. For example, (Liu *et al.* 2016) and (Bao *et al.* 2017) demonstrated that modifying SiO₂ NPs with chelating agents, such as EDTA or mercaptoamines, greatly enhances their selectivity and capacity for Pb²⁺ and Cu²⁺ removal. These studies show that the role of silica is not only structural but also chemical, as the functional groups introduced provide metal-binding sites capable of forming stable complexes.

Similarly, (Awual *et al.* 2016a) embedded selective ligands into mesoporous silica to remove Cu²⁺, demonstrating that tailored organic groups can significantly increase affinity and capacity. The introduction of large-ring ligands into silica frameworks, as reported by (Awual *et al.* 2015; Awual *et al.* 2016b), enabled highly selective removal of Cs⁺ and Se⁴⁺, indicating a clear progression toward ion-selective material design. (Alotaibi *et al.* 2017) developed iron-

supported green nanosilica that achieved high As removal efficiency and could be reused up to six times, demonstrating improvements in sustainability and operational practicality. Likewise, hierarchical magnesium silicate structures synthesized by (Huang *et al.* 2017a; Huang *et al.* 2017b) provided template-free removal of Zn^{2+} , highlighting the tunability of silica-based materials in achieving tailored morphology and function.

Further advancement was shown by (Yang *et al.* 2017a), who developed $\text{SiO}_2@\text{LDH}$ nanocomposites capable of efficiently adsorbing U(VI) due to the presence of multiple oxygen-containing functional groups, showing how layered structures improve accessibility and binding.

In recent years, mesoporous silica nanoparticles (MS NPs) have become a popular and adaptable heavy metal removal approach (Nguyen *et al.* 2019). Silica-based metal oxide nanoparticles for heavy metal adsorption possess shape-shifting at several oxidation states, tractable pore size, distinct surface area, high biocompatibility, and flexible surface modification and are non-toxic and eco-friendly adsorbents (Da'na, 2017; Li *et al.*, 2021a). MS NPs, for example, can be easily recovered and reused as adsorbents (Meky *et al.* 2024). Furthermore, SiO_2 NPs hold significant potential for providing cost-effective and environmentally friendly solutions to mitigate heavy metal pollution in water sources.

In comparison to other widely used nanomaterials in water remediation, SiO_2 NPs demonstrate distinct advantages that strengthen their applicability. For example, Fe_3O_4 nanoparticles are valued for their magnetic separation capability, but they are prone to oxidation and aggregation, which reduces long-term performance. Coating Fe_3O_4 with SiO_2 improves chemical stability, dispersibility, and provides functionalizable surface groups for selective heavy metal binding (Khosravi *et al.* 2019). Furthermore, research shows that SiO_2 NPs have evolved from simple high-surface-area adsorbents to engineered platforms functionalized with ligands, metal oxides, or magnetic cores, enhancing their capacity, selectivity, and reusability. This reflects a clear scientific progression in silica nanotechnology from passive supports to multifunctional nanocomposites optimized for heavy-metal remediation (Khosravi *et al.* 2019).

4.2 Organic Pollutant Degradation

Significant adverse environmental impacts have also resulted from the discovery or production of millions of organic chemicals, including dyes, insecticides, personal care items, and pharmaceuticals (Lu and Astruc, 2020). The environment and the health of all organisms are at risk due to this increasing pollution, which emphasizes

the need for new methods to treat water contamination. Due to their high surface area, porosity, and superior mechanical and thermal durability, silica-based adsorbents are very successful at eliminating organic waste from water. Silica particles contain surface hydroxyl groups formed by the bonding of oxygen atoms with protons, resulting in a polar surface capable of interacting with contaminants. These interactions typically occur through mechanisms such as hydrogen bonding, dipole–dipole forces, π – π stacking, and hydrophobic interactions, depending on the pollutant and surface chemistry. In recent years, functionalized SiO_2 nanoparticles have been widely used for the adsorption of organic contaminants from wastewater (Scott, 2021).

In recent years, there has been an increasing use of SiO_2 NPs to remove organic contaminants from water. (Jing *et al.* 2013) used cetylpyridinium chloride, a cationic surfactant, to functionalize nano- SiO_2 to eliminate p-nitrophenol and naphthalene. The surfactant's dual nature enabled it to remove polar p-nitrophenol through hydrogen bonding and non-polar naphthalene through hydrophobic contact. This functionalization increases surface charge and hydrophobicity, improving the adsorption of both ionic and nonpolar molecules. (Tao and Fletcher, 2014) developed mesoporous silica-based catalysts that were functionalized with sulfonic acid to eliminate metaldehyde. Sulfonic acid groups raise surface acidity, increasing proton donation ability, which enhances the adsorption of basic molecules and can also strengthen catalytic pathways in degradation reactions by stabilizing reaction intermediates (Balati *et al.* 2015). Achieved maximal adsorption capacities of 1.92, 1.41, and 0.76 mg/g for naphthalene, acenaphthylene, and phenanthrene removal using $\text{NH}_2\text{-SBA-15/SiO}_2$ (SBA: Santa Barbara Amorphous-15; mesoporous silica sieve) composites. Amino groups introduce electron-rich functional sites that enhance π – π interactions with aromatic hydrocarbons, improving adsorption capacity. Additionally, (Li *et al.* 2017) developed adsorbents for anthracene and phenanthrene by modifying silica with polydopamine. These adsorbents have adsorption capacities of 0.367 mg/g and 0.185 mg/g, respectively. Polydopamine contributes catechol and amine functionalities, enabling π – π stacking and chelation with aromatic molecules, increasing adsorption strength. (Topuz and Uyar, 2017) functionalized mesoporous silica nanoparticles with cyclodextrins, achieving nearly double the adsorption capacity of unmodified silica. Cyclodextrins possess hydrophobic cavity structures that encapsulate aromatic pollutants via host–guest inclusion mechanisms, significantly enhancing selective adsorption. (Wang, 2017) developed a novel polyvinyl alcohol/silica nanofiber that was functionalized with sulfhydryl groups to extract bisphenol from wastewater. The sulfhydryl groups generate high-affinity interaction sites that enhance

hydrogen bonding and strengthen the adsorption of phenolic compounds.

In contrast to adsorption-based approaches, some studies focused on degradation rather than physical binding. For example, (Xu *et al.* 2017) produced ultrathin α -Fe₂O₃ nanosheets using a silica hydrogel technique and achieved a 16.4-fold faster degradation rate for bisphenol compared to commercial α -Fe₂O₃. This improvement results from increased surface area and enhanced charge separation efficiency, which promote photocatalytic reactions rather than surface adsorption. Additionally, (Shao *et al.* 2017) developed CdTe@SiO₂ (cadmium telluride) core-shell particles for the purpose of serving as a fluorescence sensor for the elimination of sulfamethoxazole, where the silica shell inhibits electron-hole recombination, improving photocatalytic response and detection sensitivity.

Aerogels have also shown remediation potential. For example, (Filho *et al.* 2017) developed a highly porous silica aerogel that effectively eliminated hydrocarbons such as pyrene, xylenes, toluene, and benzene through hydrophobic interactions. It was established that the tested aerogel showed a consistent removal effectiveness (16–18%) for all hydrocarbons under investigation, and the adsorption mechanism resulted in a reduction in mass transfer resistance. The findings from the study further indicate that silica aerogels are beneficial for the removal of aromatic pollutants, particularly in challenging situations such as petroleum spills.

The environmental stability of modified silica materials, particularly those modified with surfactants such as cetylpyridinium chloride, sulfonic acid, and polydopamine, has not been extensively tested, despite the significant progress made in the use of these materials for the removal of organic pollutants. Consequently, the primary objective of future research should be to ensure the sustainability of these modified silica nanostructures.

4.2.1 Organic Dye Removal

The discharge of organic dyes from industrial waste is a significant concern worldwide, considering their detrimental effects on the environment and human well-being. Silica nanostructures have found extensive application in the removal of a range of organic dyes, such as Acid Red 88, methylene blue, methyl orange, malachite green, safranin, orange-16 (hydrophilic), solvent blue 35 (hydrophobic), direct blue 71, reactive blue 19, Congo red, and indigo carmine. The research on silica-based dye remediation can be broadly categorized into semiconductor-assisted composites, bio-based composites, magnetic-functional systems, and functionalized hybrid adsorbents, each of which offers unique benefits and methods.

(Soltani *et al.* 2013) synthesized bio-silica/chitosan nanocomposites, achieving a remarkable maximum adsorption capacity of 25.84 mg/g for Acid Red 88. (Che *et al.* 2014) developed a silica-polyelectrolyte-iron oxide nanocomposite that successfully removed methyl orange and methylene blue through electrostatic interactions, demonstrating strong adsorption capacity even after multiple cycles. Similarly, (Yang *et al.* 2017b) developed silica@layered double hydroxide (SiO₂@LDH) nanocomposites that demonstrated a capacity of 166.1 mg/l for the elimination of methyl orange. Together, these investigations show that integrating silica with polymers or layered structures improves adsorption efficiency by increasing the number of accessible functional groups for hydrogen bonding and electrostatic attraction. Steel nanoparticles and TiO₂ membranes are some notable examples of silica-based materials used by (Tolba *et al.* 2016) and (Wilson *et al.* 2017) for the removal of methylene blue. This research shows the effectiveness of silica-based adsorbents in the removal of dyes from water.

A study done by (Dutta *et al.* 2015) demonstrated the removal of methylene blue using mesoporous silica nanoparticles coated with SnO₂ quantum dots. This cost-effective and eco-friendly nanocomposite has shown remarkable results for dye remediation, achieving complete dye removal in only 5 minutes and a maximum adsorption capacity of 73.15 mg/g. This demonstrates how the addition of semiconductor components maintains strong surface adsorption while greatly accelerating the removal rate. (Soares *et al.* 2017b) produced a magnetic adsorbent by combining iron oxide nanoparticles with a κ -carrageenan/silica hybrid, reaching a significant adsorption capacity of 590 mg/g for methylene blue. This combination showed rapid adsorption and desorption, demonstrating its effectiveness. (Han *et al.* 2016) demonstrated the potential of hydrophobic silica aerogel as an alternative adsorbent for dye remediation, achieving impressive removal capacities of 65.74 mg/g for methylene blue and 134.25 mg/g for rhodamine B. Therefore, Magnetic and aerogel-based systems offer advantages in fast pollutant uptake and simple magnetic or physical recovery that improves system reusability. (Badiei *et al.* 2014) and (Patra *et al.* 2017) modified nano-porous silica (SBA-15) using tris-(2-aminoethyl) amine, resulting in a biodegradable composite (h-GG/SiO₂; h-GG: anionic guar gum) to remove malachite green. The maximum adsorption capabilities recorded were 781.25 mg/g and 2330 mmol/g. (Mansa *et al.* 2016) demonstrated improved adsorption by altering SiO₂ NPs with glycine for the removal of malachite green. (Cho *et al.* 2016) introduced a hybrid composite designed to eliminate both hydrophilic (orange-16) and hydrophobic (solvent blue 35) dyes. These findings demonstrate that selective adsorption mechanisms such as π - π interactions, hydrogen bonding, and hydrophobic

partitioning are enhanced when silica surfaces are tuned with functional groups (such as amino, amphiphilic polymers, or biopolymers).

In another study, (Abbasi 2017) developed a magnetic chitosan/SiO₂/CNT nanocomposite to remove reactive blue 19 and direct blue 71. The maximal adsorption capacities recorded were 97.08 mg/g and 61.35 mg/g, respectively. (Krishnan *et al.* 2020) developed aminotetrazole-functionalized MgO-SiO₂ (MSNT) nanocomposites using a simple wet chemical method, focusing on their potential for detecting heavy metal ions and removing dyes. The findings indicated that MSNT effectively adsorbed acid fuchsin dye, resulting in a remarkable 78% color removal within just 2 minutes. The capacity reached an impressive 775.6 mg/g, demonstrating remarkable recoverability. (Lei *et al.* 2022) combined imidazolium-based ionic liquid ([C16VIm]⁺ [Br]⁻) with amino-functionalized SiO₂ through a Michael addition process to produce SiO₂-ionic liquid (SiO₂-PIL; PIL: polymeric ionic liquid) composites. The composites displayed enhanced anionic dye adsorption, accomplishing a peak capacity of 243.67 mg/g in a short timeframe. Popoola *et al.* (2024) conducted a study on magnetized TiO₂-supported SiO₂ NPs derived from rice husk, which served as a photocatalyst for the degradation of methylene blue dye in aqueous solution. The results of these studies show that rapid diffusion, targeted pollutant affinity, and easier post-treatment material recovery are possible when silica is combined with magnetic carriers, ionic liquids, or carbon nanotubes. In summary, various modified silica-based nanocomposites have shown impressive improvements in their ability to adsorb and quickly remove a range of organic dyes from wastewater, establishing them as highly effective possibilities for environmental remediation. Overall, a comparative approach reveals distinct trends rather than treating these studies as isolated findings: bio-based composites provide sustainability, semiconductor-assisted systems integrate adsorption and degradation, magnetic hybrids facilitate quick recovery, and functionalized silica surfaces enhance selectivity through customized chemical interactions. Modified silica nanocomposites are therefore excellent options for cutting-edge wastewater purification methods since they continuously exhibit high adsorption capacity, rapid removal kinetics, and reusability.

4.2.2 Oil Spill Removal

Since SiO₂ NPs have a large surface area, are hydrophobic, and can adsorb oil, they have demonstrated promise in cleaning up oil spills from water. These nanoparticles can improve oil absorption either by themselves or in conjunction with other substances, such as hydrophobic silica-based composites. The primary method of oil removal is the powerful attraction that exists between the hydrophobic surface of the

nanoparticles and the molecules of oil, which enables the particles to absorb and extract oil from water efficiently. For instance, fuels like crude oil and diesel have been extracted from water using silica nanoparticles modified with hydrophobic groups (Khademolhosseini *et al.* 2020; Tliba *et al.* 2025). The water can be purified by the selective adsorption of the oil by these altered particles. Because of their high porosity (80–99.8%) and high surface area (500–1200 m²/g), silica-based materials, such as mesoporous silica and silica aerogels, are especially useful at cleaning up oil spills (Dorcheh and Abbasi, 2008).

The application of silica-based nanocomposites for the separation of oil-in-water emulsions has been investigated in a number of studies. For instance, (Ahmad *et al.* 2011) created polysulfone-modified silica membranes that demonstrated enhanced antifouling behavior and a permeate flux of 17.32 L/m²·h as compared to 1.08 L/m²·h for the unmodified polysulfone membrane, while exhibiting 16 times higher permeability than unmodified membranes. Additionally, for rapid oil-water separation, (Tai *et al.* 2014) made a flexible carbon-silica composite nanofibrous membrane. The membrane showed a very high permeate flux (for example: ~3032 L m⁻²h⁻¹ for petroleum spirit) and remained robust under challenging circumstances, such as high temperatures and extremely high pH. Furthermore, by adding silica to polypropylene, (Yang *et al.* 2014) produced microfiltration membranes with superhydrophobic and superoleophobic qualities for effective oil-water separation. A graphene/silica nanosorbent with improved oil clean-up capabilities was developed by (Loche *et al.* 2016). It can absorb more than seven times its own mass in oil. Although their stability is restricted to pH 7–10, these nanocomposites exhibit significant promise for water remediation due to their high porosity, hydrophobicity, and fire resistance.

Sol-gel techniques have been employed by several researchers to create silica-based materials for oil-water separation. To successfully extract water from oil and other non-polar organic compounds, (Afzali *et al.* 2017) and (Soares *et al.* 2017a) created magnetic nanoporous graphene/silica and chitosan-silica hybrid nanosorbents. (Liu *et al.* 2017) also used the sol-gel technique to create a microcrystalline methyl cellulose-silica sponge, which showed improved adsorption capacity and mechanical strength as a result of the grafting of C=O and -CH₃ groups. Chitosan-silica hybrid materials have been studied in addition to membranes and aerogels. For instance, a sol-gel-prepared chitosan-silica/HNT (halloysite nanotube) coating demonstrated superhydrophilic and superoleophobic behavior, successfully aiding in the separation of emulsions of oil and water (Wan *et al.* 2022).

Table 1. Studies showing the remediation potential of silica-based nanomaterials in contaminated water and soil

Nanomaterial	Action	Reference
Water Remediation		
Montmorillonite/carbon (nano-absorbent) (Mt@ZrP)	Increases adsorption of Pb and Cd ions (275.6 mg/g-ZrP for Mt@ZrP vs. 196.1 mg/g-ZrP for bare ZrP)	(Zhang <i>et al.</i> 2023)
Zeolites with high silica content	Adsorption, ion-exchange, or chelation of metal ions	(Karnwal and Malik, 2024)
EDTA-modified silica-coated magnetic NPs using glutathione (Fe ₃ O ₄ -SiO ₂ -GSH MNPs)	Adsorption of divalent Pb(II): Maximum adsorption capacity varied at different temperatures, viz. 298.87 mg/g (298 K), 332.44 mg/g (303 K), and 357.37 mg/g (308 K).	(Xu <i>et al.</i> 2017)
Si NPs	Remediation of Ni (30 ppm; 70.3%) and Ni (200 ppm; 60.1%) by adsorption	(Sheet <i>et al.</i> 2014)
Green Si NPs were synthesized using leaves of <i>Oryza sativa</i> , <i>Saccharum officinarum</i> , and <i>S. ravannae</i> .	>95% adsorption of Pb (II) and Cu (II) from wastewater	(Sachan <i>et al.</i> 2021)
Cysteine-cellulose-silica composites	Adsorption of heavy metals such as Pd (II) (180.9 mg/g), and Cd (II) (130.7 mg/g)	(Mazibuko <i>et al.</i> 2024)
Phosphate-embedded Si NPs (P@SiO ₂) (nanocomposite)	Adsorption of methylene blue (76.92 mg/g)	(Nayl <i>et al.</i> 2023)
Si NPs derived from rice husk ash	Removal of nitrate ions (14.22 mg/g) from polluted water	(To <i>et al.</i> 2020)
Nano-silica AgNPs (NSAgNPs)	Removal of 99% dyes (Congo red, Eosin yellow, Bromophenol blue, Brilliant blue) at a concentration of 50 mg/L via adsorption. Other significant properties of NAAgNPs include antifouling properties and removal of <i>E. coli</i> from contaminated water. Shows good tolerance and is reusable.	(Das <i>et al.</i> 2013)
Hydrophilic carbon-NPs (HNPs) supported on silica beads (SHNPs)	Removal of Cd (II) (0.042 mmol/g), Pb (II) (0.027 mmol/g), and Ni (II) (0.055 mmol/g) from wastewater at neutral pH and low temperature (10 °C) via adsorption at 0.2 mM concentration	(Natale <i>et al.</i> 2020)
Soil Remediation		
SiO ₂ NPs	Nano-silica (1000 mg/kg) stabilises heavy metals in calcareous heavy metal-contaminated soil. It reduces levels of exchangeable and carbonate-bound fractions of Pb (8%), Cu (4.5%), Zn (7.3%), Cr (7.9%), and Ni (7.1%).	(Samani <i>et al.</i> 2024a)
Thiolated silica (SiO ₂ -SH) NPs	Reduces uptake of Pb, Cd, and Cu by pakchoi (68.03%, 92.02%, and 76.34% respectively) and lettuce (43.41%, 89.81%, and 5.76% respectively); improves soil quality by reducing heavy metal toxicity	(Lian <i>et al.</i> 2021a)
Green synthesized SiO ₂ NPs	Increases the adsorption of silicon from soil. It increases macronutrients (exchangeable cations Ca, Mg, Na, and K) and reduces micronutrients (Mn, Fe, Cu, and Zn) concentration in soil. Increases activities of dehydrogenases and peroxidases in soil, which buffer soil pH.	(Labulo <i>et al.</i> 2024)
Mesoporous SiO ₂ NPs (MCM41 and MCM48)	MCM 41 is more efficient in Hg remediation than MCM 48. They reduce Hg (25 ppm)-induced stress in <i>Vigna radiata</i> (MCM 41 at 50ppm; MCM 48 at 22 ppm) and <i>Bacillus coagulans</i> (both at 100 ppm), a probiotic soil bacterium.	(Mitra <i>et al.</i> 2023)
Nanocomposite of SiO ₂ NPs and silkworm excrement biochar (SiO ₂ NPs@BC)	Increased adsorption of Cd (73.04% with SBC vs 64.97% with BC). Improved physicochemical properties of soil, such as its pH, organic matter, and cation exchange capacity; converted Cd into more stable forms, and reduced Cd toxicity in soil.	(Peng <i>et al.</i> 2024)

To sum up, silica-based materials have shown outstanding potential for the separation of oil from water and the elimination of organic contaminants because of their adjustable qualities, which include high porosity, hydrophobicity, and mechanical stability. More investigation is necessary to assess these materials' long-term stability, scalability, and usefulness in actual industrial settings, even though many of them have shown outstanding performance in lab settings. Silica nanoparticles may be essential in combating environmental contamination and developing water remediation solutions if they continue to build.

5. APPLICATIONS OF SiO_2 NPS IN SOIL REMEDIATION

The prospective uses of SiO_2 NPs in soil remediation have drawn more attention. These nanoparticles are useful tools for restoring contaminated soils because they can efficiently absorb a variety of contaminants, such as pesticides, heavy metals, and organic pollutants. Additionally, because of their adaptability, SiO_2 NPs can be customized to target specific pollutants, increasing the effectiveness and selectivity of remediation efforts. With the growing environmental worries about soil pollution, SiO_2 NPs present a viable and sustainable method of decontaminating soil, opening the door to more efficient and environmentally friendly soil restoration techniques (Fig. 4).

5.1 Nutrient Release and Soil Fertility Enhancement

In recent years, SiO_2 NPs have attracted a lot of interest due to their possible uses in soil remediation, particularly for improving soil fertility and promoting nutrient release. Their distinct physicochemical characteristics allow them to interact with soil constituents in an efficient manner, enhancing nutrient availability and encouraging plant growth. For instance, research has demonstrated that Si-based NPs can promote nutrient cycling and uptake by enriching the rhizosphere microbial community, especially nitrogen-fixing and phosphate-solubilizing bacteria (Rajput *et al.* 2021). Introducing SiO_2 NPs has been shown to promote tomato plant growth and output by increasing nitrogen uptake by up to 27%, phosphorus uptake by 22% and potassium uptake by 8% (Ijaz *et al.* 2024b). Because of these characteristics, SiO_2 NPs are a viable soil supplement that can improve soil fertility and encourage sustainable farming methods.

SiO_2 NPs have shown great promise in reducing soil-borne illnesses and enhancing plant stress tolerance in addition to boosting fertility. For example, it has been demonstrated that SiO_2 NPs considerably lower the frequency of bacterial wilt caused by *Ralstonia*

solanacearum in tomato plants. At the highest effective concentration tested, 25 $\mu\text{g/mL}$, the nanoparticles had strong antibacterial activity and produced a 14.2 mm growth inhibition zone. Application at 150 ppm reduced pathogen populations in soil, lowered disease severity, and enhanced plant physiological responses. Treated plants showed better photosynthetic efficiency, greater accumulation of antioxidants and phenolic compounds, and upregulated expression of defence-related genes such as *PR1*, *PR5*, *PAL*, and *PDF-1.2* (Wei *et al.* 2024). In summary, SiO_2 NPs demonstrated potential for use in integrated disease control techniques by limiting pathogen development and enhancing plant tolerance against oxidative and environmental challenges.

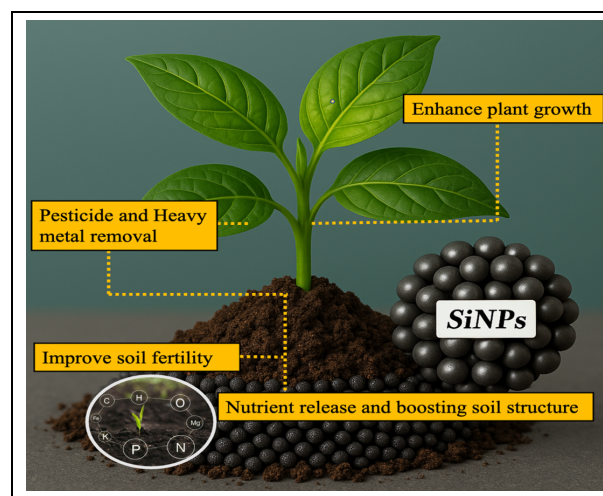


Fig. 4: Restoring contaminated soil with silica nanoparticles

5.2 Heavy Metal Remediation from Soil

Silicon dioxide-modified nanoparticles have shown promising results in stabilizing and removing heavy metals from soil. Studies demonstrate that nano-silica can convert metals like Cu, Pb, and Zn into less toxic forms. For instance, (Khan *et al.* 2019) tested different concentrations of SiO_2 NPs in Cd-contaminated soil and found that while drought-stressed plants accumulated more Cd, SiO_2 NPs treatment reduced Cd uptake in wheat grains, enhanced plant growth and photosynthesis, and mitigated plant stress, particularly at higher concentrations. Similarly, (Lian *et al.* 2019) confirmed that nano-silica reduced DTPA-extractable Cd (DTPA: diethylenetriaminepentaacetic acid) in soil. However, more research is needed to optimize application rates and improve economic feasibility. Further, thiolated nano-silica (SiO_2 -SH) significantly reduced Pb, Cd, and Cu uptake in pakchoi and lettuce—up to 92.02% for Cd and 76.34% for Cu (Lian *et al.* 2021b). SiO_2 -SH also improved soil health by lowering bulk density and increasing organic matter, microbial biomass, and cation exchange capacity, making it a safe and effective soil treatment. Supporting these findings,

(Samani *et al.* 2024b) found that the application of nano-silica in polluted calcareous soils reduced DTPA-extractable Pb, Cu, Zn, Ni, and Cr, while increasing pH and specific surface area. Metals were shifted to more stable forms (e.g., Fe–Mn oxides and organic matter-bound), with Pb showing the most significant reduction. All of these investigations suggest a single remediation process in which nano-silica enhances heavy-metal retention through functional groups (such as –SH and –OH), leading to long-term stability and reduced plant uptake. Nano-silica-based amendments are a promising, scalable, and environmentally sustainable method for enhancing soil quality in contaminated agricultural systems.

6. ENVIRONMENTAL AND HEALTH IMPACT

SiO₂ NPs, typically <100 nm in size, exist in amorphous and crystalline forms. While crystalline silica is a known Group 1 carcinogen, strongly linked to silicosis and chronic lung diseases, amorphous SiO₂ NPs are generally considered less hazardous. They are valued for their strength, stability, biocompatibility, and biodegradability, and are widely used in medicine, cosmetics, food, and agriculture (Ding *et al.* 2023). As in 2017, SiO₂ NPs were the second-largest produced nanoparticles globally, with 1.5 million tons/year and a market growth rate of 5.6%, expected to reach \$8.8 billion by 2020 (WHO, 2017; Nayl *et al.*, 2022). A survey conducted in 2022 estimated the global insulation market to be worth about \$67 billion, of which an astounding \$29.75 billion is expected to grow to a massive economy of \$110.6 billion and \$48.69 billion, respectively, by 2032, with a growth rate of 5.2% between 2022 and 2032 (Dey and Maji, 2025).

6.1 Occupational Exposure and Health Risks

Human exposure to silica nanoparticles (SiO₂ NPs) can cause a series of biological reactions, such as oxidative stress, inflammation, and organ-specific toxicity, particularly when inhaled at work. A growing body of research indicates that amorphous SiO₂ NPs are not entirely physiologically inert, despite the fact that they are frequently regarded as safer than their crystalline counterparts. For instance, (Guo *et al.* 2013) demonstrated that mice co-exposed to SiO₂ NPs and cadmium chloride (CdCl₂) showed increased oxidative stress markers along with increased cadmium accumulation in the liver and kidneys, suggesting that SiO₂ NPs can worsen the toxicity of co-existing environmental contaminants. Similar to this, (Feng *et al.* 2018) documented cardiovascular damage in rats exposed to lead acetate and SiO₂ NPs at the same time, underscoring the possibility of synergistic negative effects. Some studies also suggested that human exposure, especially via inhalation, can lead to oxidative stress, inflammation, and organ-specific toxicity (Guo *et*

al. 2021). This emphasizes the significance of stringent occupational safety regulations and ongoing research to safeguard human health as well as to direct the safe development and use of silica nanoparticles in industrial and clinical settings.

6.2 Ecotoxicity and Environmental Persistence

Environmentally, SiO₂ NPs can persist in soil and water, altering microbial activity and reducing soil fertility. In aquatic systems, they may bioaccumulate and cause oxidative stress in organisms (Ale *et al.* 2021). Their chemical stability, resistance to deterioration, and slow dissolution rates all contribute to their environmental persistence and raise concerns regarding long-term ecological effects. The necessity for long-term monitoring, environmental risk assessment, and the development of standards for the safe use and disposal of SiO₂ NPs is highlighted by the potential for bioaccumulation as well as changes in microbial diversity and metabolic activity. Furthermore, SiO₂ NPs may intensify their ecotoxicological effects by interactions with other environmental contaminants, such as organic pollutants or heavy metals, resulting in synergistic toxicity in soil and aquatic environments.

6.3 Mechanism insights into toxicity

The nanoscale physicochemical characteristics of SiO₂ NPs, such as particle size, shape, surface area, crystallinity, and surface chemistry, play a major role in determining their toxicity. The surface silanol groups (Si–OH), which can interact with cell membranes and denaturize membrane proteins, break lipid bilayers, and change membrane permeability, are a significant contributor (Book *et al.* 2019; Rubino *et al.* 2019). These silanol groups have a higher density at the nanoscale than in bulk silica, which increases their reactivity with biological molecules and environmental elements (Ambrosone *et al.* 2014). Furthermore, SiO₂ NPs can produce reactive oxygen species (ROS) from strained siloxane rings or surface radicals, which can cause oxidative stress, lipid peroxidation, mitochondrial dysfunction, and the activation of proinflammatory pathways like NF-κB (Gazzano *et al.* 2012; Zhang *et al.* 2012; Duan *et al.* 2014). Exposure to SiO₂ NPs has been demonstrated to cause oxidative DNA damage in lung fibroblast and bronchial epithelial cells, decrease intracellular antioxidants such as glutathione (GSH), and impair cellular metabolism (Petrache *et al.* 2015; Awashra *et al.* 2023). Furthermore, depending on the particle size, morphology, dose, and type of target cell, these nanoparticles might cause autophagy and death through ROS-mediated signaling pathways such as MAPK/Bcl-2 and PI3K/Akt/mTOR (Guo *et al.* 2016; Duan *et al.* 2014). Additionally, recent research has shown that amorphous SiO₂ NPs can cause mitochondrial fission through ROS/Ca²⁺/DRP1 signaling, which

contributes to epithelial apoptosis and strengthens the oxidative stress cycle (Li *et al.* 2022).

According to (Rubino *et al.* 2019) and (Petrache Voicu *et al.* 2015), even amorphous SiO₂ NPs, which are frequently thought to be biocompatible, can cause cellular, organ-specific, and systemic toxic effects under certain conditions, especially at high concentrations, prolonged exposure, or in conjunction with other environmental stressors. Surface reactivity, ROS production, redox imbalance, and activation of autophagy/apoptosis pathways all contribute to these consequences, underscoring the necessity of thorough risk assessment in both occupational and environmental situations.

7. CONCLUSION

Although SiO₂ NPs offer significant potential across various sectors, including agriculture, medicine, and environmental management, their extensive use raises concerns regarding possible adverse effects on the environment and human health. The impacts of SiO₂ NPs on water, soil, ecosystems, and human health are intricate and varied, with both advantages and disadvantages to take into account. Further investigation is necessary to completely comprehend the long-term effects of SiO₂ NPs exposure, create safer production techniques, and put in place efficient regulatory frameworks. Responsible utilization of SiO₂ NPs for safe and sustainable technological breakthroughs requires weighing their advantageous applications against their possible hazards.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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