ACCSCIENCE PUBLISHING

Explora: Environment and Resource

REVIEW ARTICLE

Titanium: Metal of the future or an emerging environmental contaminant?

Supplementary File

Table S1. Largest titanium (Ti) reserves and an overview of the global supply chain

	Ti reserve[a]		Supply chain[b]			
Country	Ilmenite (thousand metric tons)	Rutile (thousand metric tons)	Ti mineral production (metric tons of TiO_2)	Percentage of total (%)	Ti sponge production (metric tons of TiO_2)	Percentage of total (%)
China	200,000	-	3,400,000	36	120,000	57
Australia	160,000	24,000	790,000	8	-	-
India	85,000	7,400	-	-	250	0.1
South Africa	63,000	8,300	995,000	10	-	-
Brazil	43,000	1,200	-	-	-	-
Madagascar	40,000	-	414,000	4	-	-
Norway	37,000	-	468,000	5	-	-
Canada	31,000	-	430,000	5	-	-
Mozambique	14,000	-	1,108,000	12	-	-
Ukraine	5,900	2,500	411,000	4	-	-
Senegal	-	-	491,000	5	-	-
Kenya	-	-	253,000	3	-	-
Japan	-	-	-	-	35,000	17
Russia	-	-	-	-	27,000	13
Kazakhstan	-	-	-	-	16,000	8
Saudi Arabia	-	-	-	-	3,700	2
United States	-	-	-	-	500	0.2
Other countries	26,000	400	740,000	8	-	-
World total	700,000	48,000	9,500,000	100	210,000	100

Notes: [a]Source from the United States Geological Survey.[1] [b]Source from Bhutada.[2]

Table S2. Distribution of different forms of titanium in soil and aquatic environments

Forms of titanium	Distribution in soil and aquatic environments	References
Ilmenite ($FeTiO_3$)	In igneous rocks, sediments, and beach sands	3
Rutile (TiO_2)	In metamorphic rocks and igneous rocks	4
Anatase (TiO_2)	In some igneous and metamorphic rocks	5
Particulate titanium (forms of TiO_2 particles)	As solid particles suspended in water	6
Titanium dioxide (TiO_2)	In the form of fine particles	7
Complexes with organic matter	Complex with organic matter in water, forming colloidal complexes	8

Table S3. Plant–titanium (Ti) interactions: Studies investigating the direct addition of titanium dioxide (TiO_2) for plant benefit

Plant Species	Concentration	Treatment technologies	Effects	References
Vigna unguiculata	62 – 125 mL/ha	Field trials conducted to investigate foliar TiO_2 as a growth promoter	Yield increased by 8 – 50%; foliar and pod disease severity reduced	9
Salvia officinalis	0 – 80 mg/L	Three-week trial with impacts on germination and plant growth	Germination increased, but there was no effect on shoot, root, and seedling elongation and biomass	10
Allium cepa	0 – 50 mg/L	Impact on germination, seedling growth, and hydrolytic and antioxidant enzymes	Enhanced germination, growth, and enzyme activity at low doses; inhibition at higher doses	11
Solanum lycopersicum	0 – 1,000 mg/kg	Field study to conduct trials on Ti translocation	Foliar application of lower doses increased growth; no effect at higher doses	12
Fragaria ananassa	0 – 150 mg/kg	Growth and yield under low light conditions	Yield, hardness, and pigments increased with foliar application; decreasedphenolics	13
Vicia faba	0 – 0.03%	Impact on growth and tolerance to saline stress	Dose-dependent positive impacts on growth under control and saline stress conditions	14
Triticum aestivum	-	Fertigation impacts on drought tolerance of four cultivars evaluated	Fertigation under stress enhanced leaf thickness and longevity, and increased pigment content and photosynthesis	15
Coriandrum sativum	0 – 400 mg/L	Impacts on growth and nutritional content under hydroponic conditions	Lower doses increased growth and nutrient uptake; higher doses triggered oxidative stress	16
Dracocephalum moldavica	0 – 250 mg/L	Impact on growth and tolerance to saline stress	Dose-dependent alleviation of saline stress	17
C.sativum	0 – 160 mg/L	Effect of seed priming on biochemistry, morphology, and growth under cadmium stress	TiO_2 decreased in planta cadmium content, improved biochemistry, and increased growth	18
Vicia faba	10 – 20 mg/L	Impact on growth and tolerance to saline stress	Reduced osmotic and salinity-induced stress	19
Melissa officinalis	0 – 100 mg/L	Impact on tolerance to drought stress	Increased resistance to drought stress by increased photosynthesis, photosynthetic pigments, antioxidant activity, nutrient absorption, and decreased reactive oxygen species	20
Sesamum indicum	0 – 15%	Impact on growth and biochemistry under heat stress	Dose-dependent increased growth and positively impacted biochemistry under heat stress	21

Table S4. Plant–titanium interactions: Studies involving the use of plant extracts to synthesize nanoscale titanium dioxide

Plant species	Concentration	Preparation methods	Effects	References
Eclipta prostrata	-	Leaf extract used for nanoparticle (NP) synthesis	Particles characterized by FTIR, XRD, AFM, and FESEM	22
Plant extracts	-	Using plant and other biological extracts for NP synthesis	Review article	23
Moringa oleifera, *Triticum aestivum*	0 – 80 mg/L	*Moringa oleifera*-derived NPs were synthesized, characterized, and applied to *T. aestivum* infected with leaf blotch	Dose-dependent suppression of disease damage and an increase in plant growth	24
Buddleja asiatica, *T. aestivum*	0 – 80 mg/L	*Buddleja asiatica*-derived NPs were synthesized, characterized, and applied to *T. aestivum* under saline stress	Dose-dependent increase in growth and improvement in biochemistry	25
Puccinia striiformis, *T. aestivum*	0 – 80 mg/L	*Puccinia striiformis*-derived NPs were synthesized, characterized, and applied to *T. aestivum* under pathogen stress	Dose-dependent modulation of biochemistry that alleviates pathogen damage	26
Glycine max	0 – 50 mg/L	Biosynthesized nanoscale TiO_2 (aloe vera extract) added to soybean	Dose-dependent alleviation of salinity stress observed	27

Abbreviations: AFM: Atomic force microscopy; FESEM: Field emission scanning electron microscopy; FTIR: Fourier transform infrared spectroscopy; XRD: X-ray diffraction.

Table S5. Selected references on the potential remediation methods of titanium (Ti) contamination in soil and aquatic environments

Environmental matrix	Initial concentration	Test plant and/or amendment	Detailed description	References
Soil environment				
Soil	-	Pedunculate oak (*Quercus robur* L.)	• The concentration of Ti content in wood accumulated up to 1,900 mg/kg	28
Ilmenite soil	2.3 – 31.3%	Beach morning glory (*Ipomoea biloba*)	• The concentration of Ti content in leaves accumulated 135 – 1,521 mg/kg	29
Mineralized area soil	-	Horsetail (*Equisetum* spp.)	• The average Ti content in the above-ground parts of the plants reached 460 mg/kg, and the maximum concentration reached 1,200 mg/kg	30
V-Ti magnetite mine tailings soil	104.5±8.31 mg/kg	*Pongamia pinnata* (inoculated with *Bradyrhizobium Liaoning ense* PZHK1)	• Inoculation of PZHK1 increased plant *P. pinnata* biomass by an additional 44.76% • Inoculation also increased the metal accumulation capacity and superoxide dismutase activity of *P. pinnata* • The bioconcentration factor of *P. pinnata* after inoculation increased from 0.05 to 0.13	31
	-	*Pongamia pinnata*	• Soil rapidly available nutrients, enzyme activity, and microbial carbon and nitrogen contents increased • *Rhizobium* and *Nordella* were identified as the keystone taxa	32
	-	*Pongamia pinnata*	• Soil microbial communities were reshaped by *P. pinnata*	33
Red gypsum, produced by the neutralization of wastewaters with limestone from a TiO_2 plant	6,245±90 mg/kg	Poplar cuttings, cucumber, pepper, cabbage, and lettuce	• Although the total Ti of gypsum was high, the Ti contents after CaCl2 extraction were below the limit of quantification • The highest Ti content was found in lettuce leaves, and the lowest in poplar leaves • There is a potential risk of Cr content in cucumber fruits	34
TiO_2 NPs contaminated soil	100 and 1,000 mg/kg	*Suaeda glauca* and *Brassica campestris*	• *Suaeda glauca* has stronger resistance to TiO_2 NPs compared to *B. campestris* • Phytoremediation removes approximately 60% of TiO_2 NPs from the soil	35
Aquatic environments				
Natural water	5 mg/L	$FeCl_3$ or poly-aluminum chloride	• The removal rate of TiO_2 NPs reached beyond 90% • The average particle size of the suspended TiO_2 NPs after treatment decreased from 145 nm to 43 nm • Increasing the ionic strength in the media sink enhanced the removal rate of TiO_2 NPs	36
Four synthetic waters of different concentrations and organic properties (hydrophilic/hydrophobic)	10 mg/L	Commercial poly-aluminum chloride	• The removal of TiO_2 NPs in all types of water samples was >90% • Hydrophobic water requires a higher dose of coagulant than hydrophilic water to obtain the same removal of TiO_2 NPs • The main mechanism for TiO_2-NP removal is charge neutralization	37
Artificial groundwater and artificial surface water	10 – 100 mg/L	Iron chloride, iron sulfate, and alum	• The removal rates of TiO_2 NPs in groundwater were >90% for all coagulants • In surface water, the removal rates of $FeSO_4$ and $Al_2(SO_4)_3$ were >90%, whereas for $FeCl_3$, the removal rate was less than 60% • The removal of TiO_2 NPs was not effective at high zeta potential (>35 mV)	38

(Cont'd...)

Table S5. ***(Continued)***

Environmental matrix	Initial concentration	Test plant and/or amendment	Detailed description	References
Natural surface water	1 mg/L	Commercial poly-aluminum chloride coagulant/flocculant	• The removal rate of TiO_2 NPs reached over 99% by coagulation, flocculation, and sedimentation • The Ti removal rate was 98% in low turbidity water (1.91±0.36 NTU) and 99% in medium turbidity water (63.33±5.37 NTU)	39
Distilled water	0 – 10 mg/L	Fe_3O_4-SiO_2 and Fe-C-SO_3H composites	• Under ideal conditions, 99.7% TiO_2-NP removal can be achieved in 30 min	40
Natural water	5 – 125 mg/L	Poly-*L*-lysine glasses covered with lecithin	• The average removal rate is 58% • No coagulation, flocculation, or precipitation required	41
Dye water	2 mg/L	Modified cellulose nanofiber-based polyvinylidene fluoride microfiltration membrane	• The retention rate of Fe_2O_3 NPs exceeds 99% • It can effectively adsorb positively charged crystalline violet dyes	42
Natural water	5 mg/L	0.10 µm and 0.45 µm microfiltration membranes	• The removal rate of TiO_2 NPs reached more than 90% • Addition of 1.0 mM phosphate enhances the removal rate of TiO_2 NPs in 0.10 µm microfiltration membranes	36

Supplementary information

1. Toxicity of TiO_2 to animals and human health

Several medical studies showed that a 2-year exposure of rats to high levels of fine TiO_2 caused the formation of lung tumors.[43,44] A growing body of evidence suggests the potentially toxic effects of TiO_2 nanoparticles (NPs) in biota through inhalation, ingestion, and injection.[45] Although the tumorigenic effect of fine TiO_2 has been questioned,[46] collective reports suggest that TiO_2, particularly those in nanoscale form, are more toxic than fine particles. TiO_2 NPs were found to be 40-fold more potent in the induction of lung inflammation and damage than fine TiO_2.[47] The European Food Safety Authority[48] declared that TiO_2 could no longer be deemed safe when used as a food additive. For example, studies have shown that TiO_2 NPs can lead to sublethal effects on earthworm survival and reproduction.[49-51]

Animals, including humans, are exposed to Ti through ingestion, respiration, or direct contact, with most studies focused on TiO_2 NPs. Dietary routes include the ingestion of animals of a lower trophic level,[52] plants containing TiO_2,[53] and in humans, food additives with TiO_2 NPs in their formulation.[54,55] Studies focused on exposure by respiration or direct contact have a broad range of experimental designs. In aquatic environments, the particles are suspended in water where organisms might ingest or inhale TiO_2 NPs.[52] Terrestrial animals inhale airborne particles,[56] while in humans, dermal exposure occurs through contact with particles embedded within formulations of personal care products, such as sunscreen.[57] Numerous toxicological studies have been conducted to assess the effects of TiO_2 NPs exposure on biota.[58-60] Despite the vast number of studies, the toxicity of TiO_2 NPs on animals and humans, as well as the underlying mechanisms of action, remain topics of debate and continue to be investigated.[45]

1.1. Aquatic species

Different models demonstrated that TiO_2 NPs exist in water with concentrations ranging from 0.7 to 100 µg/L in coastal zones.[61,62] Importantly, Mueller and Nowack[62] calculated that doses <1 µg/L are not expected to cause adverse effects (predicted no effect concentration). Toxicity studies have focused on fish, crustaceans, mollusks, nematodes, frog embryos, and coral, with most doses being sublethal but at high concentrations in the parts per million (mg/L) range.[59,63] A small number of representative studies for each group are noted in the following sections.

1.2. Fish

In *Scophthalmus maximus* (flatfish turbot), citrate-coated TiO_2 NPs impaired lipid metabolism at sublethal concentrations with a daily intake of 1.5 mg/kg fish weight administered through pellets. Higher numbers of lipid droplets (lipid storage organelles) in the liver were associated with smaller citrate-coated TiO_2 (anatase, 5 nm), and decreased lipid droplets were linked to larger particles (anatase/rutile, 25 nm).[64] Different exposure routes (TiO_2 at 30, 50 or 100 mg/L in water where fish were submerged or through the intake of clamworms treated with TiO_2 NPs) led to similar accumulation and distribution

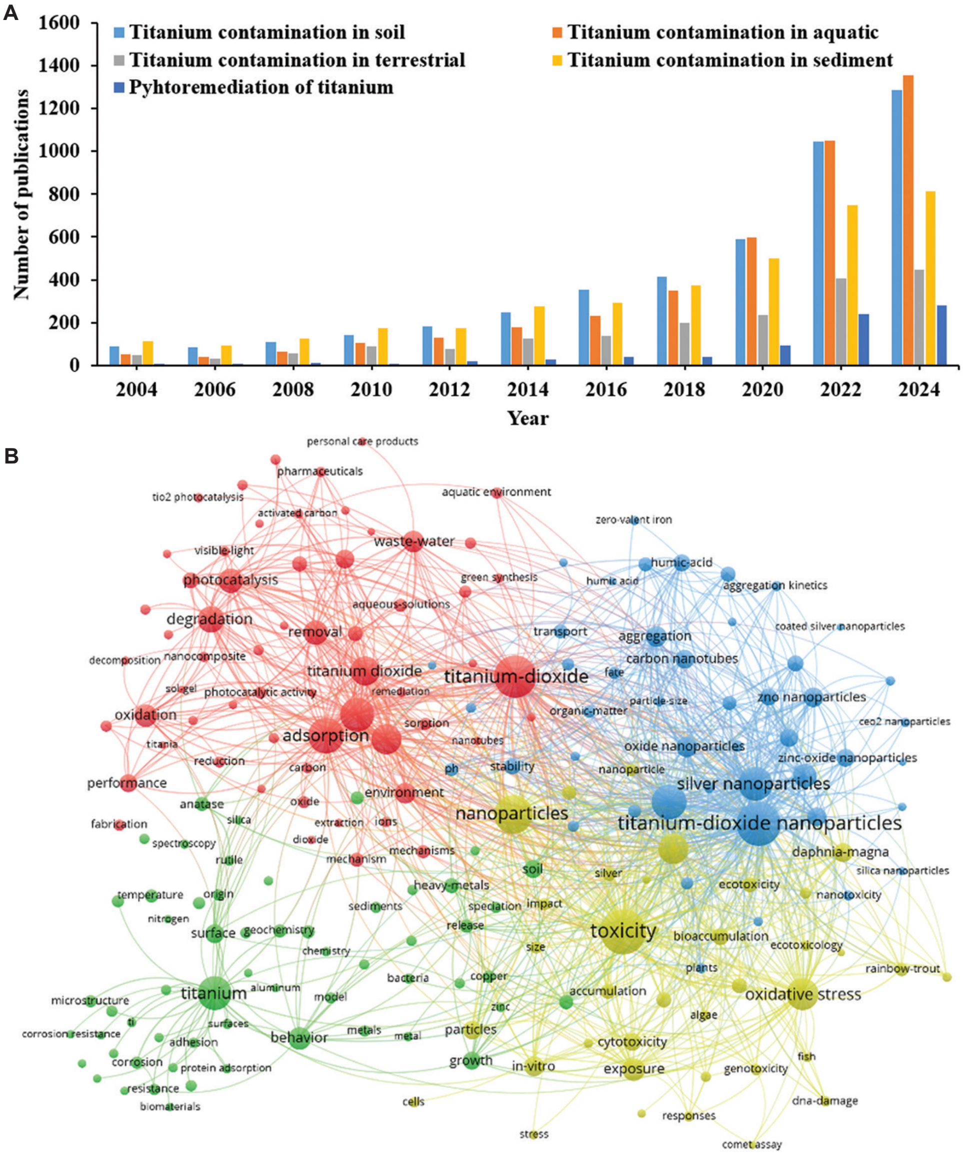

Figure S1. Methodology figures. (A) The number of publications on titanium-related studies over the last 20 years. (B) The number of publications on the topic of the removal of water pollution using titanium (IV) dioxide over the last 20 years, and the keyword co-occurrence map showing the most investigated topics.

patterns in juvenile turbot. Most Ti accumulation was in the turbot's gill, intestine, and stomach, with less in skin, liver, and muscular tissue. The protein content was significantly reduced in both exposure pathways of TiO_2 NPs at 100 mg/L, and the amount of lipid increased, compromising the fish's nutritional value.[52] Lei *et al.*[65] exposed *Daniorerio* (zebrafish) embryos to TiO_2 NPs alone at 0.1 mg/L or in combination with pentachlorophenol (PCP). TiO_2 NPs alone did not show adverse impacts on the thyroid hormones. While PCP downregulated the neurodevelopmental marker genes, TiO_2 in combination with PCP did not alter the neurobehavioral defects in zebrafish larvae but promoted the PCP-induced thyroid endocrine disruption. In a study with low/relevant environmental levels, a nanocomposite of reduced graphene oxide and Ti (RGO/TiO_2) exhibited minimal toxicity to zebrafish embryos at concentrations up to 30 μg/mL.[66] The body length, heartbeat counts, and hatching percentages remained unchanged. However, the toxicity was concentration dependent, and high concentrations (above 0.125 mg/mL) resulted in cardiotoxicity and abnormalities in the developmental embryos. In *Oreochromis niloticus* (Nile tilapia), anatase TiO_2 NPs at 0.05 and 0.1 mg/L did not cause neurotoxicity, but induced DNA damage;[67] and

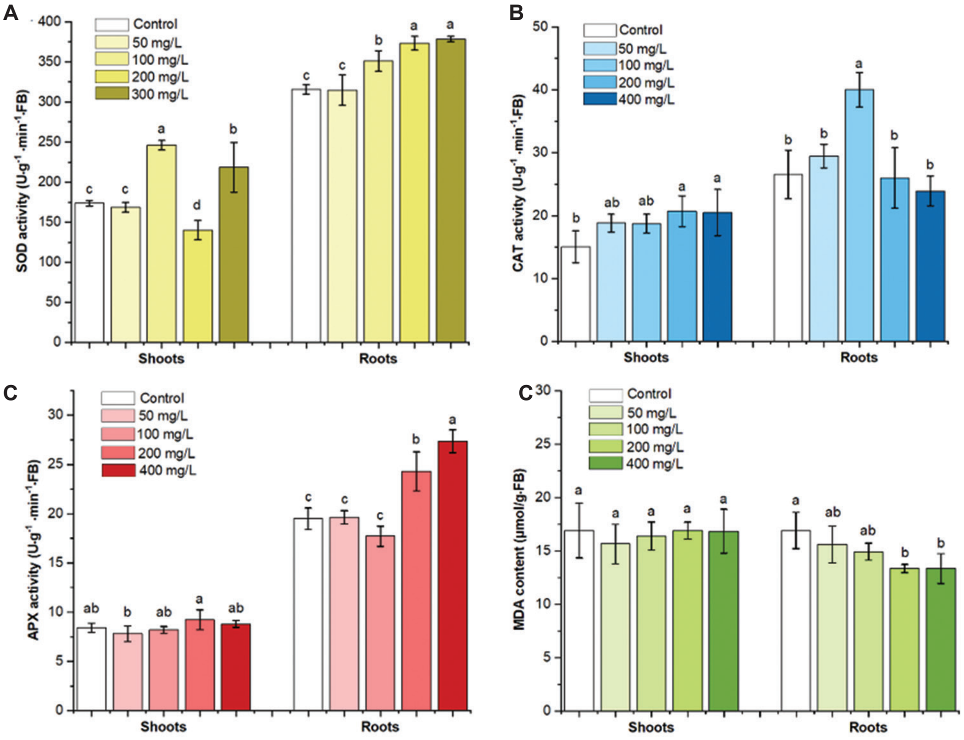

Figure S2. The effects of TiO_2 at different concentrations on the activities of various antioxidant enzymes and lipid peroxidation in coriander shoots and roots: (A) Superoxide dismutase (SOD) activity; (B) Catalase (CAT) activity; (C) Ascorbate peroxidase (APX) activity; and (D) Malondialdehyde (MDA) content. Modified from Hu *et al.*[16] Copyright 2020 Elsevier.

at 0.1, 0.5, and 1 mg/L, altered liver and intestine cells were evident under continuous exposure.[68] Hou *et al.*[59] compiled a list of studies on different fishes, such as *Cyprinus carpio* (common carp), *Carassius auratus* (goldfish), *Oryzias latipes* (Japanese rice fish), and *Pimephales promelas* (fathead fish), mostly in freshwater-like media, showing that high Ti concentrations induced toxic effects, including variations in body weight, alterations to enzymatic activity, and oxidative stress (lipid peroxidation).

1.3. Crustaceans, mollusks, and other benthic zone species

Daphnia magna has been a model organism to assess both the toxic effects of TiO_2 NPs as well as the protective capabilities of TiO_2 NPs against ultraviolet (UV) radiation. Anatase TiO_2 NPs' toxicity to *D. magna* was shown to be dependent on the radiation intensity. After 8 h of sunlight exposure, the concentration causing 50% mortality (LC_{50}) was 139 μg/L under 100% exposure to natural sunlight, 778 μg/L at 50% intensity, and more than 500 mg/L at 10% sunlight exposure.[69] Conversely, 80:20 anatase/rutile TiO_2 NPs from 0.1 to 10 mg/L protected *D. magna* from UV-B light (200 $\mu W/cm^2$) by absorbing and blocking the radiation.[70] As a popular test model for ecotoxicological tests, there are many studies available on *D. magna* and a more limited number for other crustaceans. Several studies have shown species-dependent effects and variable indices of toxicity from TiO_2NP exposure.[44,59,63,71]

Mussels feed in the bottom layer of water bodies (benthic zone) and are capable of filtering large volumes of water. Their behavior is crucial for maintaining water quality; they are vulnerable to pollutants present in the benthic zone and are valuable bioindicators of environmental health. In *Mytilus galloprovincialis* (Mediterranean mussel), TiO_2 NPs (0.05 – 5 mg/L) destabilized the lysosomal membrane in the immune cells (hemocytes) and digestive glands. These NPs induced the accumulation of neutral lipids and increased the enzymatic activity of catalase (CAT) and glutathione in the digestive gland without affecting the CAT or glutathione S-transferase activities in the gills.[72] Leite *et al.*[73] reported that after 28 d of exposure to rutile TiO_2 (0, 5, 50, or100 μg/L), *M. galloprovincialis* exhibited histopathological effects at both low (18°C) and high (22°C) temperatures, while biochemical impacts were observed only at the higher temperature. Exposure to a concentration of TiO_2 at 100 μg/L for 14 d in a medium simulating ocean warming (28°C) down regulated the messenger RNA expression related to the byssus production and impaired the byssal threads' mechanical strength of *Mytilus coruscus*.[74,75] Wang *et al.*[76] found that the effects of TiO_2 (0.1, 1.0, and 10 mg/L) were size (25 and 100 nm) and concentration dependent. They observed that the highest concentration (10 mg/L) and the smaller particle size (25 nm) of TiO_2 NPs were more toxic to *M. coruscus* hemocytes. Likewise, Huang *et al.*[77] observed that TiO_2 NPs induced oxidative stress in *M. coruscus*, with similar effects under seawater acidification.

1.4. Rodents and humans

Pure Ti, a biocompatible material widely used in orthopedical implants, is inert. Hip and knee replacements are often made with pure Ti or alloyed with other elements (e.g., Al, V, and Nb).[78] Unlike the highly stable Ti and Ti-alloys used in medical implants, Ti-based nanomaterials are more reactive. Characteristics such as size, shape, and crystalline structure of TiO_2 NPs influence the bioavailability and severity of TiO_2 NP's toxicity.[57] *In vitro* studies with human cell lines showed that the anatase structure exhibited higher cytotoxicity than a mixture of anatase/rutile or rutile alone.[79,80] Moreover, a study that assessed the toxicity of different TiO_2 shapes (bipyramids, rods, and platelets) reported that toxicity was influenced by shape and light exposure, with rods after light exposure being the most harmful to cells.[81] Li and Tang[82] discussed the toxicity of TiO_2 NPs to mammalian organs, noting that TiO_2 NPs damage tissues and disrupt organ function. They also identified common mechanisms of toxicity, such as TiO_2 inducing oxidative stress, damaging organelles, and activating inflammatory responses. However, similar to aquatic species, the impacts of Ti NPs on rodents and humans vary significantly with dose and exposure scenario.

Supplementary information

2. Removal of titanium from aquatic environments

Phytoremediation, a sustainable and environmentally friendly technology, is widely recognized for its effectiveness in eliminating diverse pollutants from soil and aquatic environments.[83-85] Among the various phytoremediation techniques, phytoextraction is the most employed approach.[86-88] This technique primarily involves the extraction of environmental pollutants by accumulating plants and their subsequent translocation to the above-ground tissues, effectively eliminating contaminants from the specific environment after plant harvesting.[89-91] In the case of Ti removal, certain plant species, namely pedunculate oak (*Quercus robur* L.), horsetail (*Equisetum* spp.), and beach morning glory (*Ipomoea biloba*), exhibit substantial potential for phytoremediation owing to their exceptional ability to accumulate Ti.[92,93] While the implementation of phytoremediation for Ti removal lacks extensive engineering cases, some high-biomass tree species, such as poplar and willow trees, are extensively utilized for phytoremediation of metal elements.[34,94,95]

The application of TiO_2 NPs for the remediation of soil heavy-metal contamination has gained attention due to their unique properties, such as high redox potential, presence of interconnected pores, eco-friendly nature, and polymorph crystalline size/shapes, as discussed earlier.[96] Notably, plants possess the ability to simultaneously absorb TiO_2 NPs and the pollutants adsorbed onto them.[97] However, earlier studies predominantly focused on investigating the phytotoxicity of TiO_2 NPs, primarily through hydroponic experiments, neglecting the potential of plants to remove TiO_2 NPs.[98-100] More recently, several studies were carried out to explore the efficiency of phytoremediation using TiO_2 NPs as contaminants. For example, Song *et al.*[35] discovered that the halophyte plant species *Suaeda glauca* exhibited an ability to eliminate 60% of TiO_2 NPs from the soil with aTiO_2-NP concentration of 1,000 mg/kg.

The accumulation and removal of TiO_2 NPs in the aquatic environment (as pollution) has garnered significant attention (Figure S1B).[38,101,102] Similar to other NPs, Ti NPs can be remediated through various technologies, such as coagulation, flocculation, sedimentation, adsorption, and membrane filtration.[36,41,103] Conversely, addressing water pollution using the photocatalytic or absorption properties of TiO_2 has also been discussed by researchers in a number of recent publications.[104-106]

2.1. Coagulation, flocculation, and sediment

Coagulation, flocculation, and sedimentation are vital processes employed in conventional drinking-water treatment, offering efficient and cost-effective removal of various types of particulate matter and soluble inorganic compounds.[107] The neutralization of positive and negative charges onNPsis the key mechanism in coagulation for TiO_2-NP removal, achieving a removal efficiency of 90% or higher.[37] The overall efficiency of TiO_2-NP removal is influenced by factors such as the coagulant type and dosage, water quality, and other parameters. Studies have investigated coagulants, such as alumand those based on iron and aluminum, for TiO_2-NP removal.[37,38,102] Notably, previous researchers have achieved high removal rates of NPsusing significant amounts of coagulants, such as alum at concentrations up to 50 mg/L.[38] For low (1.91 ± 0.36 NTU) and medium (63.33 ± 5.37 NTU) turbidity natural waters, Ti removal rates of 98% and 99%, respectively, were obtained.[39] Interestingly, hydrophobic constituents in water necessitate a higher coagulant concentration compared to hydrophilic constituents to achieve the same TiO_2-NP removal rate.[37] According to the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory, the interparticle repulsive forces diminish as the media ionic strength increases due to the compression of the bilayer.[108-110] Consequently, the addition of NaCl or $CaCl_2$ enhances the removal of TiO_2 NPs.[36] Furthermore, the removal effectiveness is closely related to the zeta potential. Zhang *et al.*[36] found that TiO_2-NP removal was highest (>90%) when the zeta potential value was <10 mV, while removal was poor (<60%) when the zeta potential exceeded 35 mV.

2.2. Adsorption

The process of adsorption and adhesion is determined by various forces, such as van der Waals forces, double-layer forces as described by the DLVO theory, and non-DLVO interactions, including hydraulic forces, spatial forces, steric hindrance, and magnetic interactions.[111,112] Inexpensive materials, including activated carbon, halloysite, and iron oxide magnetic particles, are currently utilized for NP removal.[113-115] Adsorption materials possessing magnetic properties, particularly magnetic halloysite and iron oxide magnetic particles,[115] offer the advantages of easy separation and reusability after recovery. Furthermore, TiO_2 NPs can be encapsulated by polydopamine and liposomes and subsequently removed through adsorption onto poly-*L*-lysine glasses coated with lecithin.[41] This method does not require coagulation, flocculation, and sedimentation, and shows an average removal rate of 58%.[116] Magnetic NPs hold great potential for TiO_2-NP removal due to their larger specific surface area. For example, Fe_3O_4-SiO_2 and Fe-C-SO_3H composites can achieve 99.7% TiO_2 removal within 30 min.[40] The authors observed that among all the mentioned techniques, the composite/magnetic NP-induced remediation was the most efficient for the removal of TiO_2 in practice.

2.3. Membrane filtration

Membrane filtration, particularly nanofiltration, is widely recognized as one of the most effective technologies for contaminant removal.[117] Nanofiltration technology can filter out 99.9% of NPs in a solution.[118] However, nanofiltration membranes possess small pore sizes and exhibit lower efficiency in water treatment.[119] Conversely, microfiltration technology offers higher water treatment efficiency and can potentially achieve 99% removal of NPs.[42] Nevertheless, the high concentration of NPagglomeration may result in a reduction of membrane pore size and pore blockage, thereby diminishing the efficiency of water treatment.[120] For example, Zhang *et al.*[36] discovered that microfiltration (0.45 μm) alone for TiO_2-NP removal could yield higher removal rates compared to the combined coagulation-flocculation-precipitation-microfiltration process, but with lower water treatment efficiency. They also observed that the addition of 1.0 mM phosphate enhanced the removal of TiO_2 NPs using 0.10 μm microfiltration membranes.

2.4. Other technologies

Other techniques, including biofilm, activated sludge, and artificial wetlands, have demonstrated effectiveness in removing NPs from aqueous environments.[121-123] However, there is still relatively little information on Ti removal with these techniques. Notably, when employing bio-related water treatment methods, it is crucial to closely monitor the removal efficiency of other indicators, considering the biological toxicity and antibacterial properties associated with high concentrations of TiO_2 NPs.[123] For example, the presence of 50 mg/L TiO_2 NPs significantly diminished microbial diversity within activated sludge, resulting in a decrease in total nitrogen removal efficiency from 80.3% to 24.4%.[124]

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