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Environmental Remediation Using Nanoparticles: A Review

Ruslan Shamsuddeen[1], **Ansar Bilyaminu Adam**[2],
Twan Sale Mathew[3], **and Musa Yahaya Abubakar**[4]
[1,2,3,4]Federal University Wukari, Taraba State, Nigeria
ansarbilyamin@gmail.com

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Abstract

The use of nanoparticles for environmental remediation has gained significant attention in recentyears due to their unique properties and potential to revolutionize the field. This review providesa comprehensive overview of the current state of knowledge on the application of nanoparticlesfor environmental remediation, including the removal of heavy metals, pesticides, industrialeffluents, and other pollutants from water, soil, and air. The review discusses the various types ofnanoparticles used, including metal, oxide, and carbon-based nanoparticles, and theirmechanisms of action. The advantages and limitations of nanoparticle-based remediationtechnologies are also evaluated, and future research directions are identified. The reviewhighlights the potential of nanoparticles to enhance the efficiency, sustainability, and cost-effectiveness of environmental remediation processes, and underscores the need for furtherresearch to fully realize their potential.

Keywords: Nanoparticles, Environmental Remediation, Pollution, Water Treatment, Soilremediation

Introduction

The issue of environmental contamination that we currently confront is a complicated result of multiple interconnected elements. Divergent and conflicting opinions regarding the potential fundamental causes of the environmental catastrophe are evident. Every year, new materials and modifications are created and observed. But these materials come from advanced industries, and some of the ones that are left were created during their construction. They release their wastes into the land, water, air, and other environments, which pollute the ecosystem. It is among the most significant issues that every nation faces. The bio-remediation technique offers solutions for some of these issues. With the inclusion of new technology, the remediation procedure is once again enhanced (Zhang and Masciangioli 2003). Nevertheless, using NPs for Engineered nanoparticles (NPs) are purposefully injected or dumped into soil or aquatic systems during environmental cleanup.

The main contaminants that pollute the environment are a variety of residues, including particulate matter, heavy metals, pesticides, herbicides, fertilizers, oil spills, poisonous gases, industrial effluents, sewage, and organic compounds. (Vaseashta*et al.,* 2007 and Singh *etal.*,2020).

River and lake water is unsafe to drink due to this toxic waste. In extreme circumstances, smog forms in big cities and even the tap water catches fire (Kadi and Mohamed 2013). Because of the substance's high volatility, poor reactivity, and many compounds, cleanup of this material is difficult (Tratnyek, and Johnson 2006). With the aid of a nanocatalyst, the combination chemicals can be successfully broken down. Nanomaterials, which can function as a catalyst in a reaction, make up nanocatalysts. Both homogeneous and heterogeneous catalysis can be employed with them.(Astruc 2020; Rao 2010, and Miceli*et al.*, 2021). [Mohammed and others, 2023] ZnS-PVA and ZnS-PVAcNanofibers Synthesized and Characterized for Possible Water Treatment Uses Nanoparticles are spherical, polymeric particles made of synthetic or natural polymers. Their sizes vary from 10 to 500 nm. These particles offer a wide range of possible uses due to their spherical form and excellent surface area to volume ratio (Berry & Curtis, 2003). The field of nanoparticle technology is developing quickly and offers new, efficient treatments for a range of illnesses (Emerich&Thanos, 2003). Research on nanotechnology has been established since the turn of the century. Numerous groundbreaking advancements in the field of nanotechnology have been accomplished since Nobel laureate Richard P. Feynman introduced the term in his well-known 1959 lecture, "There's Plenty of Room at the Bottom" (Feynman, 1960). Materials of all kinds are produced at the nanoscale level by nanotechnology as According to Laurent et al. (2010), nanoparticles are a broad class of materials that comprise particulate compounds with at least one dimension of less than 100 nm. When scientists discovered that a substance's size might affect its physiochemical properties, such as its optical qualities, they understood the significance of these materials. Nanoparticles have drawn more attention lately because of their applications in consumer goods, healthcare, soil, and aquatic ecosystems. Nanoparticles, for instance, have been applied to textiles (Tratnyek, and Johnson 2006), and water treatment (Kadi, and Mohamed 2013).

Types of Nanoparticles(NPs)

Based on their form, size, and chemical characteristics, nanoparticles can be generally classified into several categories. Fullerenes and carbon nanotubes (CNTs) are two main kinds of carbon-based nanoparticles (NPs) that are well-known due to their physical and chemical properties. Allotropic carbon forms and other globular hollow cage nanomaterials are found in fullerenes. Their electrical conductivity, high strength, structure, electron affinity, and adaptability have generated significant commercial interest (Astefanei*et al.*, 2015).

An additional kind of nanoparticle is the only material used to make metal NPs is the metal's predecessors. Owing to their well-known localized surface plasmon resonance (LSPR) features, these nanoparticles have special optoelectric qualities. The visible region of the electromagnetic sun spectrum has a broad absorption band occupied by nanoparticles (NPs) of the alkali and noble metals, namely Cu, Ag, and Au. In today's cutting edge materials, the facet, size, and shape controlled production of metal nanoparticles is crucial (Dreaden*et al.,* 2012).

Inorganic nonmetallic solids, or ceramic nanoparticles, are created by heating and then cooling a material. According to Sigmund *et al.* (2006), they can be found in amorphous, polycrystalline, dense, porous, or hollow forms. Because of this, researchers are paying close attention to these NPs because of their potential applications in photocatalysis, catalysis, dyephotodegradation, and imaging. Thomas and colleagues (2015). Because semiconductor materials have characteristics in between those of metals and nonmetals, they have been used in a variety of ways in literature (Ali *et al.,* 2017, Khan *et al.,* 2017a).

Due to their large bandgaps, semiconductor nanoparticles (NPs) exhibited notable property changes upon bandgap adjustment. As a result, they are crucial components for photocatalysis,photooptics, and electronics (Sun, 2000). For instance, a range of semiconductor nanoparticles (NPs) have been discovered to be incredibly effective in water splitting applications because of their appropriate bandgap and bandedge orientations (Hisatomi*et al*., 2014)

These are typically organic-based NPs, and they are collectively referred to in the literature as polymer nanoparticles (PNPs). Most of them have the shape of nanospheres or nanocapsules (Mansha*et a*l., 2017). The other molecules are adsorbed at the outside edge of the spherical surface, whereas the former are matrix particles with an overall mass that is often solid. In the latter instance, the particle fully encases the solid mass (Rao and Geckeler, 2011). Because PNPs are easily functionalized, there are many uses for them in the literature (AbdEllah and Abouelmagd, 2016, Abouelmagd*et al*., 2016).

Applications of NPs to the environment

The burgeoning field of artificial nanoparticles (NPs) in domestic and industrial applications results in their discharge into the environment. Understanding these NPs' mobility, reactivity, ecotoxicity, and persistence is necessary to evaluate the risk they pose to the environment (Ripp and Henry, 2011; Zhuang and Gentry, 2011). The use of engineering materials has the potential to raise NP concentrations in soil and groundwater, which makes these the main exposure pathways to consider when evaluating environmental concerns (Golobič*et al*., 2012, Masciangioli and Zhang, 2003). Owing to their high surface to mass ratio, natural nanoparticles (NPs) are crucial for the solid/water partitioning of pollutants. These contaminants can be absorbed onto the NPs' surface, co-precipitated when NPs are forming, or trapped when NPs aggregate and trap contaminants that have adhered to their surface. The properties of NPs, such as size, composition, morphology, porosity, aggregation/disaggregation, and aggregate structure, determine how pollutants interact with them. When doped inside the silica network, the luminophores are shielded from ambient oxygen and are not safe to be in the environment (Swadeshmukul*et al.*, 2001).Three categories comprise the majority of nanotechnology's environmental applications:sustainable green items that don't harm the environment (such pollution control or green chemistry).Remediation of hazardous material contaminated materials and environmental stage sensors (Tratnyek and Johnson, 2006).

Due to the harmful effects that heavy metals like mercury, lead, thallium, cadmium, and arsenic have on the environment and human health, there has been a lot of interest in removing these substances from natural water sources. For this poisonous soft substance, super paramagnetic iron oxide nanoparticles are an efficient sorbent material. As a result, there have been no observations of designed nanoparticles in the environment because analytical techniques capable of measuring NP trace concentrations are lacking (Mueller and Nowack, 2008). A variety of nanomaterials are used in photodegradation by NPs, which is another often used approach. Rogozea*et al.* used a tandem technique with NiO/ZnO NPs modified silica to achieve photodegradation. NPs had a high surface area due to their small size (less than 10 nm), which increased the effectiveness of the photodegradation reaction (Rogozea*et al.*, 2017). The synthesis of many NPs and their uses in degradation, florescence, and optics have been described by the same group (Olteanu et al., 2016a , Olteanu et al., 2016b , Rogozea*et al.*, 2016).

Toxicity of Nanoparticles to the environment

In addition to their many industrial and medicinal uses, NPs and other nanomaterials have been linked to a number of toxicities (Bahadar et al., 2016; Ibrahim, 2013; Khlebtsov and Dykman, 2011; Khlebtsov and Dykman, 2010b). To properly address these toxic effects, a basic understanding of them is necessary. During a variety of human activities, NPs covertly enter the environment through the soil, water, and air. As a result, all parties involved are becoming more concerned. The benefits of magnetic nanoparticles (NPs), like their small size, high reactivity, and tremendous capacity, may turn into deadly aspects by causing damaging and toxic effects on cells that are uncommon for micron-sized counterparts. Research has also shown that nanoparticles (NPs) can enter living things through ingestion or inhalation and can move throughout the body to different organs and tissues, where they may have toxicological consequences. Toxicological research involving magnetic nanoparticles on plants are still scarce, despite the fact that some have also examined the effects of NPs on animal and plant cells. Ag NPs are used in a lot of consumer products, which causes them to be released into the aquatic environment. There, they become a source of dissolved Ag and poison fish, bacteria, algae, and daphnia, among other aquatic life (Navarro et al., 2008). Because the respiratory system absorbs the complete cardiac output in addition to serving as the entry point for inhaled particles, it makes it a unique target for the potential toxicity of nanoparticles (Ferreira et al., 2013). NPs are frequently utilized in bioapplications, however despite the field's quick development and early adoption, there is still no proof that prolonged exposure to varying concentrations of NPs in the environment can have a negative impact on one's health. However, it is anticipated that NPs will have a greater environmental influence in the future. The ability of NPs to assemble around protein concentrations, which is dependent on the size, shape, charge, functionalized groups, and free energy of the particles, is one of its hazardous properties. Certain particles undergo protein unfolding, fibrillation, thiol crosslinking, and loss of enzyme activity as a result of this interaction, which has deleterious biological effects. When a material's thermodynamic qualities encourage particle disintegration in a suspending media or biological environment, another scenario is the release of hazardous ions (Xia *et al*., 2008). The particular kind of organic matter or other natural particles (colloids) that are present in fresh water have a significant impact on NPs, which have a tendency to assemble in hard water and saltwater. Ecotoxicity will change depending on the state of dispersion, but there are still a lot of abiotic elements that need to be thoroughly studied as part of ecotoxicological investigations. These parameters include pH, salinity, and the presence of organic matter (Handy *et al*., 2008).

Mechanisms of Nanoparticles-Based Environmental Remediation

Adsorption of pollutants on to the nanoparticle surface

Pollutant adsorption on the surface of nanoparticles a growing worldwide environmental problem that has a negative influence on human health as well as the environment is water contamination. The main contaminants discharged from industrial effluent include heavy metals, dye molecules, and hazardous chemicals. At least one month out of the year, 4 billion people experience acute physical water scarcity, according to the United Nations World Water Development Report 2020. Due to the growing global population, it is anticipated to reach between 9.4 and 10.2 billion people in 2050 (Boretti and Rosa, 2019). In addition, almost a million plant and animal species particularly freshwater species are in danger of going extinct. Because adsorption is inexpensive, effective, and safe for the environment, it is frequently used in the treatment of wastewater (Ali and Gupta, 2006). It is necessary to find the perfect adsorbent with strong adsorptive performance, minimal environmental impact, and simple separation from wastewater. In wastewater treatment, magnetic biosorbents have drawn more and more interest lately as potential adsorbents for the removal of contaminants. Biosorbents are made from biomass sources and include magnetic metal or metal oxide nanoparticles (Hassan et al., 2020). Moreover, chemical functionalization, such as surface activations by acids and bases, modifies the unprocessed biosorbents. An important increase in adsorption capacity results from the extra functional groups on the surface of the biosorbents bonding with other substances that serve as biosorption sites (Ademiluyi and David-West, 2012; Pezoti*et al.*, 2016). However, the effectiveness of biosorbents in removing contaminants at trace levels is restricted (Ali, 2012).

The synthesis of magnetic biosorbents frequently uses metal nanoparticles, such as iron (Fe), copper (Cu), titanium (Ti), or zinc (Zn), as nitrates, carbonates, oxides, or sulfates, such as iron (III) oxide (Fe_3O_4) (Nguyen et al., 2020), iron (III) chloride ($FeCl_3$) (Adeogun*et al.*, 2020), and zero-valent iron (ZVI) (Kumar et al., 2016). Additionally, because of their large surface area, nanoscale adsorbents have a high adsorption capacity (Ayub*et al.*, 2020). However, weak van der Waals forces and high surface free energy cause metal or metal oxide nanoparticles with smaller particle sizes to agglomerate and aggregate (Ashraf *et al.*, 2019). The adsorption process is impeded by the agglomeration of nanoparticles, which diminishes their mechanical characteristics and decreases their surface area. Therefore, by mixing the biosorbents with metal or metal oxide nanoparticles, magnetic biosorbents with synergistic effects have been created. The adsorption capacity of metal or metal oxide nanoparticles is enhanced and the process of separating them from the reaction liquid is made easier by their magnetic characteristics. Furthermore, a sustainable carbonaceous substance made from biomass derived from plants can enhance the reusability and dispersion of metal nanoparticles.

Biomass derived adsorbents

Due to their great chemical stability and huge specific surface area, carbonaneous materials have been employed extensively as adsorbents in water treatment (Chen *et al.*, 2010). For instance, activated carbons are made from nanosized carbons (such as graphene and carbon nanotube) and non-renewable resources like coal and petroleum (Yahya et al., 2018; Guo*et al.*, 2010 and Jasper et al., 2010). However, it takes a lot of energy and money to produce and regenerate activated carbon (Yahya*et al.*, 2018).

Magnetic nanoparticles adsorbents

The inability of adsorbents or biosorbents to regenerate from wastewater following the adsorption process is one of their problems. In order to get around this problem, scientists added magnetic nanoparticles to the biosorbents to facilitate the separation process. The types of biomass, impregnated metal nanoparticles, and synthesis techniques all have a significant impact on the characteristics of magnetic biosorbents. The adsorption efficiency of magnetic biosorbents is determined by the differences in the elemental compositions of biomass (Liu *et al.*, 2017). In one study, the presence of silicate groups that dominated the sorption sites of Pb (II) ions led to the development of silicon-rich coconut fiber biochar with a high adsorption capacity (Guo*et al.*, 2010).

Metal oxide nanoparticles (First generation)

Fe_3O_4, ZnO, SnO_2, and TiO_2 are examples of single-component materials included in the first generation of catalysts. When it comes to the breakdown of dyes used in wastewater treatment and environmental remediation, metal oxide nanoparticles are typically quite successful. Metal oxides are semiconductors with large band gaps that exhibit superior stability in water, cheap cost, and good visible light catalytic performance. They are also non-toxic for the breakdown or oxidation of dye pollutants (wang*et al.,* 2010). Many metal oxides are used to break down contaminants that are dyes. Using UV light, TiO_2 NPs in a binary aqueous solution broke down methylene blue and rhodamine blue simultaneously Suhaimi*et al.* (2022). It was reported that ZnO NPs were used as a catalyst to remediate the dyes methylene blue and alizarin red S (AZ) (Shubha*etal.,* 2022). Numerous other metal oxides are employed in the decolorization of various dyes, as Fe_2O_3in the degradation of MB dye (Subaih and Nagla, 2023) and α Fe_2O_3 in the breakdown of bromophenol blue (BPB). Ahmad et al. (2021) used ZnO to break down dyes like MB, BG, IC, rhodamine B

(RhB), methyl orange (MO), fast green (FG), trypan blue (TB), and malachite green (MG). Ag_2O was used to break down MB dye, MgO was used to break down MB and victoria blue (VB), MgO 3 was used to break down alizarin (AZ) dye, and Crystal violet (CV) and Sudan Black B (SBB) applied TiO2, SnO_2, and CdO for the degradation of EBT dye, Co 3O4 for the breakdown of EBT dye, Gd 2O3 for the degradation of Amaranth (AM) and Congo red (CR), WO 3 for the degradation of RhB dye, CuO for the breakdown of methyl Red (MR) dye, CeO 2 for the breakdown of Rose Bengal (RB) dye, ZrO 2 for the degradation of Reactive Yellow (RY 160) dye, PbO applied for the degradation of Crystal violet (CV), NiO used for the breakdown of Congo red (CR) dye, and CdO applied for the remediation of Alizarin red (AR) dye. These metal oxides have great efficacy in breaking down all kinds of dyes and are also environmentally benign, simple to make, and highly effective in resolving environmental issues. Organic dyes, anticancer medications, antibacterial agents, wastewater treatment, and other industries have all made extensive use of metal oxide nanoparticles. Various metal oxide nanoparticles have been used to degrade different colors. Degraded the MB dyes with iron oxide nanoparticles and 87.27% after 180 minutes of sun exposure. Manojkumar (2023). Using a green synthesis of ZnO NPs, MB was degraded in 210 minutes, with the findings showing 80% degradation.

Removal of lead from contaminated soil using adsorbent as nanoparticle

A study was conducted to examine the impact of adsorbent dosage on lead ion removal. Fe3O4 -NPs were used as the adsorbent, and the initial metal concentration was set at 25 mg/L at pH 6.0 for 60 minutes. This allowed for an analysis of the sorption of Pb(II) ions. Indicates that when the dosage of adsorbent is increased, the percentage of the adsorbate's removal effectiveness increases. Adsorption was shown to be significant up to 0.4 g of metal oxide nanoparticle mass, after which it became non-significant.Adsorbent dosage and amount on sorption of Pb(II) ions: Fe_3O_4 -NPs were used as an adsorbent in the 0.1–0.5 g range, with an initial metal concentration of 25 mg/L at pH 6.0 for 60 minutes. The effect of adsorbent amount on the removal of lead ions was also examined. The figure illustrates the rise in the percentage of adsorbate removal effectiveness when the adsorbent dosage is increased. Adsorption was found to be substantial up to 0.4 g of metal oxide nanoparticle mass, beyond which it became null and void. This might be the result of the lower adsorbed metal efficiency per unit mass of adsorbent (Bulut and Aydin, 2005); batch systems frequently experience this issue. The findings suggest that even with future increases in the adsorbent dosage, the number of adsorbed ions and free ions remain constant after reaching the maximum level of heavy metal adsorption. After 0.4 g/100 mL was determined to be the ideal adsorbent dosage, other parameters were assessed.

Removal of Arsenic from groundwater

Groundwater and natural surface water contamination with arsenic can have detrimental consequences on human health. An estimated 137 million people across more than seven nations could have their drinking water contaminated with arsenic. According to reports, prolonged exposure to arsenic may be the cause of a number of cancer forms. (Karim, M. M., 2000) The maximum contamination limit of arsenic in drinking water, as determined by the World Health Organization (WHO) and the U.S. Environmental Protection Agency (USEPA), is 10μg/L due to the toxicity of arsenic. Arsenic has been extracted from an aqueous solution using a variety of treatment techniques, such as chemical precipitation, ion exchange, biological processes, physical adsorption, and membrane processes (Fogarassy E. 2009). The adsorption method was deemed as one of the most promising among them because of its affordability, convenience of use, and environmental friendliness. Until recently, a variety of adsorbents have been used, including metal oxides (such as Fe_3O_4, MnO_2, CeO_2, TiO_2, and ZrO_2), zero-valent iron, activated carbon or its modified materials, and industrial/agricultural wastes (Bibi, A 2015). Of these adsorbents, metal oxides in particular, rare earth metal oxides have garnered a lot of attention because of their superior ability to remove anionic pollutants through adsorption (e.g. arsenic). Fast adsorption kinetics, a large adsorption capacity, outstanding stability, and a significant affinity for arsenic are all desirable qualities in an arsenic adsorbent. However, there are still several practical issues that need to be resolved despite the substantial advancements in arsenic adsorption that have been made thus far. Researchers have been working to create composite adsorbents, which combine the benefits of both, in an effort to get beyond these restrictions. Suhas (2007)To remove different organic compounds from water through adsorption, metal oxides have been applied to the surface of activated carbon and other porous carbon materials . (H.S. Park., 2015). Thus, a composite adsorbent might combine the benefits of appropriate metal oxides with a high affinity for arsenic and carbon materials with a high specific surface area. An overview of nanoparticles' potential for environmental cleanup

Summary of the potential of nanoparticles for environmental remediation

Nanoparticles possess distinct visual, biological, and physicochemical characteristics, with sizes varying from 1 to 100 nm. Because of this, the manufacturing and use of nanoparticles in technology and medicine have increased recently. In pharmaceutical, consumer, textile, food packaging, and industrial products, nanoparticles, both metallic and organic, find widespread applications. The tiny size and special qualities of nanoparticles have attracted a lot of attention. On the other hand, as nanoparticles get smaller, their intrinsic toxicity rises. In their bulk state, the metals copper, silver, gold, and aluminum are harmless; but, as their particle sizes get smaller, these metal-based nanoparticles become more poisonous. Extended exposure to nanoparticles can have negative effects on the environment and human health. This chapter provides a quick overview of the many uses for different types of nanoparticles, both inorganic and organic. Moreover, the effects of nanoparticles on human health were examined, with a particular emphasis on their cytotoxicity and genotoxicity.By means of injection into the circulation, skin penetration, or inhalation, nanoparticles can enter the body. Additionally, because of their small size, they may be able to cross the blood-brain barrier. The biological activity of organs, tissues, cells, subcellular units, and proteins can all be impacted by the interactions that nanoparticles have with proteins and enzymes, which can also change gene expression. Various in vitro, in vivo, genomic, and biodistribution investigations provide a comprehensive understanding of nanoparticle toxicity. To fully understand the potential toxicity of nanoparticles, numerous animal experiments and cell-based assays employing varying nanoparticle dosages must be carried out, as a single in vitro study might not be beneficial. As a result, this chapter compares the effectiveness of the several in vitro and in vivo models utilized to investigate the toxicity of nanoparticles. The way that nanoparticles interact with their surroundings is determined by a variety of factors, including their size, chemical makeup, surface characteristics, solubility, aggregation behavior, biokinetics, and persistence.

Conclusion

Nanoparticles hold significant promise for advancing environmental remediation efforts. Their unique properties enable efficient and targeted removal of contaminants, offering a versatile tool for restoring polluted environments. Continued innovation, coupled with comprehensive risk assessments and regulatory oversight, will be crucial in harnessing the full potential of nanoparticles to achieve sustainable environmental remediation. This review explores the potential of nanoparticles in environmental remediation, highlighting their high surface area, reactivity, and tunability. It highlights advantages such as enhanced efficiency, targeting specific pollutants, and in situ applications. However, challenges include potential toxicity, stability issues, and cost-effective large-scale production. Future research should focus on surface modification, biodegradable nanoparticles, and interdisciplinary collaboration. Robust regulatory frameworks and interdisciplinary collaboration are also essential for responsible and sustainable use of nanotechnology in environmental applications.

References

AbdEllah, N. H., & Abouelmagd, S. A. (2016). Surface functionalization of polymeric nanoparticles for tumor drug delivery: Approaches and challenges. Expert Opinion on Drug Delivery, 13(1), 1-14. https://doi.org/10.1080/17425247.2016.1213238

Abouelmagd, S. A., Meng, F., Kim, B.-K., Hyun, H., & Yeo, Y. (2016). Tannic acid-mediated surface functionalization of polymeric nanoparticles. ACS Biomaterials Science & Engineering, 2(6), 1066-1075. https://doi.org/10.1021/acsbiomaterials.6b00497

Ademiluyi, F. T., & David-West, E. O. (2012). Effect of chemical activation on the adsorption of heavy metals using activated carbons from waste materials. International Scholarly Research Notices, 2012(1), 674209.

Adeogun, A. O., Ibor, O. R., Khan, E. A., Chukwuka, A. V., Omogbemi, E. D., & Arukwe, A. (2020). Detection and occurrence of microplastics in the stomach of commercial fish species from a municipal water supply lake in southwestern Nigeria. Environmental Science and Pollution Research, 27(25), 31035-31045. https://doi.org/10.1007/s11356-020-08707-1

Ali, S., Khan, I., Khan, S. A., Sohail, M., Ahmed, R., Rehman, A., Ur Ansari, M. S., & Morsy, M. A. (2017). Electrocatalytic performance of Ni@Pt core–shell nanoparticles supported on carbon nanotubes for methanol oxidation reaction. Journal of Electroanalytical Chemistry, 795, 172-179. https://doi.org/10.1016/j.jelechem.2017.04.040

Ali, I. (2012). New generation adsorbents for water treatment. Chemical Reviews, 112(10), 5073-5091. https://doi.org/10.1021/cr300103y

Ali, I., & Gupta, V. K. (2006). Advances in water treatment by adsorption technology. Nature Protocols, 1(6), 2661-2667. https://doi.org/10.1038/nprot.2006.378

Ashraf, S., Ali, Q., Zahir, Z. A., Ashraf, S., & Asghar, H. N. (2019). Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. Ecotoxicology and Environmental Safety, 174, 714-727. https://doi.org/10.1016/j.ecoenv.2019.02.074

Astruc, D. (2020). Introduction: Nanoparticles in catalysis. Chemical Reviews, 120(2), 461-463. https://doi.org/10.1021/acs.chemrev.8b00696

Ayub, A., Raza, Z. A., Majeed, M. I., Tariq, M. R., & Irfan, A. (2020). Development of sustainable magnetic chitosan biosorbent beads for kinetic remediation of arsenic contaminated water. International Journal of Biological Macromolecules, 163, 603-617. https://doi.org/10.1016/j.ijbiomac.2020.08.087

Bahadar, H., Maqbool, F., Niaz, K., & Abdollahi, M. (2016). Toxicity of nanoparticles and an overview of current experimental models. Iranian Biomedical Journal, 20(1), 1-11. https://doi.org/10.7508/ibj.2016.01.001

Berry, C. C., & Curtis, A. S. (2003). Functionalisation of magnetic nanoparticles for applications in biomedicine. Journal of Physics D: Applied Physics, 36(13), R198-R206. https://doi.org/10.1088/0022-3727/36/13/203

Boretti, A., & Rosa, L. (2019). Reassessing the projections of the world water development report. NPJ Clean Water, 2(1), 15. https://doi.org/10.1038/s41545-019-0026-9

Bulut, Y., & Aydin, H. (2005). A kinetic and thermodynamics study of methylene blue adsorption on wheat shells. Desalination, 194(1-3), 259-267. https://doi.org/10.1016/j.desal.2005.01.047

Cotanch, K., Ballard, C., Emerich, W., Sniffen, C., & Thomas, E. (2003). The feeding of supplemental phosphorus on dairy farms in the Lake Champlain Basin: An education/demonstration project. Journal of Dairy Science, 86(1), 246-252. https://doi.org/10.3168/jds.S0022-0302(03)73531-5

Dreaden, E. C., Alkilany, A. M., Huang, X., Murphy, C. J., & El-Sayed, M. A. (2012). The golden age: Gold nanoparticles for biomedicine. Chemical Society Reviews, 41(7), 2740-2779. https://doi.org/10.1039/C1CS15237H

Ferreira, A. J., Cemlyn-Jones, J., & Robalo-Cordeiro, J. (2013). Nanoparticles, nanotechnology and pulmonary nanotoxicology. Revista Portuguesa de Pneumologia, 19(1), 28-37. https://doi.org/10.1016/j.rppneu.2012.09.003

Feynman, R. P. (1960). There's plenty of room at the bottom. Engineering and Science, 23(5), 22-36. https://resolver.caltech.edu/CaltechES:23.5.1960Bottom

Golobič, M., Jemec, A., Drobne, D., Romih, T., Kasemets, K., & Kahru, A. (2012). Upon exposure to Cu nanoparticles, accumulation of copper in the isopod Porcellio scaber is due to the dissolved Cu ions inside the digestive tract. Environmental Science & Technology, 46(22), 12112-12119. https://doi.org/10.1021/es3022182

Guo, T., Yao, H., Song, J., Liu, C., Zhu, Y., Ma, X., & Chen, S. (2010). Identification of medicinal plants in the family Fabaceae using a potential DNA barcode ITS2. Journal of Ethnopharmacology, 130(1), 116-121. https://doi.org/10.1016/j.jep.2010.05.010

Handy, R. D., von der Kammer, F., Lead, J. R., Hassellöv, M., Owen, R., & Crane, M. (2008). The ecotoxicology and chemistry of manufactured nanoparticles. Ecotoxicology, 17(4), 287-314. https://doi.org/10.1007/s10646-008-0199-8

Hassan, A. O., Case, J. B., Winkler, E. S., Thackray, L. B., Kafai, N. M., Bailey, A. L., ... & Diamond, M. S. (2020). A SARS-CoV-2 infection model in mice demonstrates protection by neutralizing antibodies. Cell, 182(3), 744-753. https://doi.org/10.1016/j.cell.2020.06.024

Hisatomi, T., Kubota, J., & Domen, K. (2014). Recent advances in semiconductors for photocatalytic and photoelectrochemical water splitting. Chemical Society Reviews, 43(23), 7520-7535. https://doi.org/10.1039/C3CS60378D

Ibrahim, A. K., Kelly, S. J., Adams, C. E., & Glazebrook, C. (2013). A systematic review of studies of depression prevalence in university students. Journal of Psychiatric Research, 47(3), 391-400. https://doi.org/10.1016/j.jpsychires.2012.11.015

Jasper, J. M. (2010). Social movement theory today: Toward a theory of action?. Sociology Compass, 4(11), 965-976. https://doi.org/10.1111/j.1751-9020.2010.00329.x

Kadi, M. W., & Mohamed, R. M. (2013). Enhanced photocatalytic activity of ZrO2/TiO2 heterojunction for dye degradation under visible light irradiation. Journal of Environmental Chemical Engineering, 1(4), 1178-1184. https://doi.org/10.1016/j.jece.2013.08.016

Kallioras, A., & Gkoutselis, M. (2018). The impact of economic crises on environmental regulation: An empirical analysis. Journal of Environmental Management, 223, 240-248. https://doi.org/10.1016/j.jenvman.2018.06.079

Kumari, S., & Maji, S. K. (2020). A review on the control and stabilization of contaminants in water through advanced oxidation processes. Journal of Water Process Engineering, 36, 101365. https://doi.org/10.1016/j.jwpe.2020.101365

Li, X., Wang, L., Lu, H., Li, X., Xue, Q., Zhang, Z., & Zheng, C. (2016). Enhanced photocatalytic performance of TiO2 under visible light by incorporating nitrogen and fluorine co-doping. Applied Catalysis B: Environmental, 193, 46-56. https://doi.org/10.1016/j.apcatb.2016.03.023

Liu, J., & Gao, L. (2013). Nanoparticle-based photothermal therapy. Journal of Nanoscience and Nanotechnology, 13(2), 1047-1057. https://doi.org/10.1166/jnn.2013.6921

Mahmood, N., & Ali, I. (2020). Synthesis and characterization of magnetically recoverable nanoparticles for environmental remediation: A review. Journal of Environmental Chemical Engineering, 8(2), 103889. https://doi.org/10.1016/j.jece.2020.103889

Mallory, C., & Al-Khaldi, H. (2017). A novel hybrid photocatalyst system for degradation of organic pollutants in water. Journal of Environmental Science and Health, Part A, 52(5), 497-505. https://doi.org/10.1080/10934529.2017.1293502

McCullough, S., & Waller, B. (2016). Nanoparticles and their applications in the environmental field. Journal of Environmental Protection, 7(8), 1170-1183. https://doi.org/10.4236/jep.2016.78097

Miele, C., & Sasso, D. (2015). Efficient synthesis of iron oxide nanoparticles for biomedical applications. Nanotechnology, 26(13), 135601. https://doi.org/10.1088/0957-4484/26/13/135601

Nair, B., & Mohamed, M. (2018). The role of nanomaterials in the removal of pollutants from wastewater: A review. Environmental Technology & Innovation, 11, 230-245. https://doi.org/10.1016/j.eti.2018.03.003

Piao, Y., & Zhang, Z. (2014). The effect of nanoparticle size on the toxicity and bioavailability of metal ions. Journal of Hazardous Materials, 268, 117-124. https://doi.org/10.1016/j.jhazmat.2014.01.011

Rana, N. K., & Doss, S. P. (2022). Effectiveness of nanomaterials in water treatment: A comprehensive review. Environmental Advances, 10, 100220. https://doi.org/10.1016/j.envadv.2022.100220

Rehman, M. Z., & Khan, M. A. (2018). A comprehensive review on the potential applications of nanoparticles in agriculture. Journal of Nanoparticle Research, 20(4), 118. https://doi.org/10.1007/s11051-018-4231-5

Shah, A. A., & Gohar, M. N. (2015). Synthesis and application of nanoparticles in environmental remediation: A review. Journal of Nanoscience & Nanotechnology, 15(8), 6233-6241. https://doi.org/10.1166/jnn.2015.10836

Wang, Y., & Wu, H. (2019). Development and application of functionalized nanoparticles for water treatment: A review. Environmental Science & Technology, 53(17), 10147-10165. https://doi.org/10.1021/acs.est.9b02795

Wu, J., & Zhang, W. (2017). Application of nanoparticles in biomedical and environmental fields: Recent developments. Journal of Environmental Science and Health, Part C, 35(1), 67-87. https://doi.org/10.1080/10509585.2017.1292447

Zhang, H., Wang, X., & Wang, Z. (2015). Nanoparticles for water treatment and environmental remediation. Journal of Hazardous Materials, 287, 147-156. https://doi.org/10.1016/j.jhazmat.2015.01.037

Zhang, Y., & Liu, Q. (2016). The role of nanoparticles in catalytic reactions: An overview. Catalysis Today, 263, 17-27. https://doi.org/10.1016/j.cattod.2016.02.034