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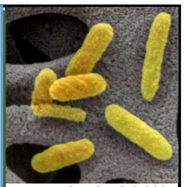

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False color SEM of *A. hydrophila*

Engineered Green Synthesized Silica-Oxide Nanoparticle for Enhanced Bioremediation of Petroleum Polluted Soil in the Niger Delta

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Abstract

The most prevalent environmental contaminants in the Niger Delta zone are petroleum hydrocarbons, and their spillage poses a serious threat to life. So many techniques have been deployed over the years to reclaim soil perturbed with petroleum hydrocarbons using nanobioremediation. The use of these nanoparticles is drawing so much attention, which could be attributed to several qualities these nanoparticles possess. These engineered green synthesized silica-oxide nanoparticles (EGSSON) are used for the enhanced degradation of petroleum hydrocarbon-polluted agricultural farm soil, thereby restoring beneficial microorganisms to the ecosystem. With the manufacturing of these environmentally friendly (EGSSON), the industrial cost for decontaminating agricultural soil might be cut down due to the availability of the plant materials used, which are productive and more efficient than other methods, which have hazardous material manufacturing, inefficient cleanup techniques, and high capital needs. Therefore, using effective, eco-friendly, and financially feasible methods is essential to establishing and achieving environmental sustainability. Because of their large size, strong chemical reactions, and catalytic properties, these nanoparticles are employed to remediate hydrocarbon-polluted soil, which has led to an increase in their use in recent decades. After calcination of bamboo leaves to create white, powdery silica-oxide particles, the silica-oxide nanoparticle is further described and put through an ecotoxicity test on microbial cells. These green synthesized silica-oxide nanoparticles, when introduced with hydrocarbon-degrading microorganisms, exhibit a nanobioremediation strategy that is cost-effective, friendly to the environment and highly sustainable.

INTRODUCTION

Due to certain changes as a result of industrialisation and urban development across the Niger Delta region, technological and economic advancements have expanded quickly. Environmental pollution and its effects on human health have significantly increased as a result of this, together with the surrounding environment, which has been devastating. Petroleum hydrocarbons remain the most spilled environmental pollutant known in the Niger Delta region, and it is estimated that for the past sixty years, over twelve million metric tons of petroleum hydrocarbons have been spilled. Likewise, this environmental pollution has affected over 200 sites across the Niger Delta, and about 5,000 samples have been collected for different laboratory analyses [1]. Over the years, scientists have employed several techniques to mitigate the effects of this hydrocarbon pollution by implementing bioremediation processes. Bioremediation is one of the most studied treatment methods, which promotes the use of microorganisms and plants to decontaminate hydrocarbon-impacted sites. Bioremediation procedure, no doubt, is effective and helps to minimise environmental impact; likewise, other techniques such as biochemical and biophysical processes have been applied for remediation [2,3]. However, these procedures require a longer treatment period, which can affect both the microorganisms and plants due to high pollutant concentration levels.

Recent years have seen a great deal of research on nanotechnology, which has the exciting ability to heal polluted environments without harming the local microflora. In terms of cost, effectiveness, and environmental friendliness, the nanobioremediation technique presents the most promising and dependable treatment technology. In agricultural soil, essential macro and micronutrients are added that encourage crops to develop healthily, which helps human health. So many man-made activities contaminate the soil with hazardous materials such as hydrocarbons, agro-chemicals, and excessive eutrophication. Nanobioremediation is a modern technique applied to clean polluted areas by accelerating the biodegradation process using nanoparticles. This process involves the use of plants and microorganisms to degrade petroleum hydrocarbons into smaller particles that are harmless to the environment [4].

One innovative and exciting technology that has shown promise is nanotechnology, which is deployed for many industrial uses such as bioremediation, the production of food, medical equipment, and electronics. The degradation of agricultural soil is a frequent environmental impact that lowers crop yields due to the uptake of heavy metals from polluted soil, which seriously harms human and animal health. Native microorganisms present in contaminated areas can be used to tackle the majority of issues pertaining to the biodegradation of harmful chemicals. Currently, there is a lot of interest in cleaning contaminated soil of pollutants utilizing very porous NPs like silica oxide. Through their phytocatalytic qualities, nanostructured carbon compounds like silicon dioxide (SiO2) and titanium (TiO2) are employed to eliminate contaminants from the environment. Numerous advantageous characteristics are provided by biologically produced NPs for the identification and breakdown of harmful contaminants. Biochar-loaded nanoparticles were employed as a new nanostructured adsorbent to remove arsenate. Recent studies have focused on creating ecologically friendly, high-cost methods like bioremediation with minimal adverse impacts in order to address this environmental issue [5].

Pollutant cleanup benefits from the combination of biological and non-biological technology. The idea of bioremediation has undergone a significant transformation with the introduction of nanotechnology, which deals with materials in the nanoscale range that have unique characteristics because of their minuscule size. Nanotechnology has drawbacks when it comes to cleaning up contaminants; however, the decontamination process's effectiveness and potential are significantly increased by nano-bioremediation [6]. Researchers have recently become interested in this relatively new approach, which uses nanoparticles to manage harmful contaminants from soil and water with encouraging results. To expedite the elimination of pollutants, various nanomaterials can be used in conjunction with microorganisms. According to Saratale et al. [7], the introduction of microbial enzymes using different nano-supports has raised a lot of dust in managing waste. In the bioconversion and remediation processes, microbial enzymes and nanomaterials are used [8].

Analyzing environmental remediation procedures that include microorganisms and silica nanoparticles, as well as the use of nanotechnology across industries, is the primary objective of this analysis. As a result of our industries' expansion and population growth, contaminants such as heavy metals and organic and inorganic chemicals have been continuously released into the environment, contaminating both surface and groundwater systems (**Fig. 1**). These pollutants are a constant threat to humans, and as such, it is necessary to eradicate them through the process of remediation [4,9]. The remediation process requires certain regulatory requirements, likewise, human and ecological risk assessment. Remediation of these pollutants can be achieved via traditional methods which can be grouped as physical, chemical and biological methods [1].

Physical method

The physical treatment method is used to extract impurities from the matrices without having the capacity to render them less hazardous or innocuous. This form of remediation is old and conventional; it's normally used to clean up water, soil, or air. The physical method, as compared to other methods, is quite expensive and not environmentally friendly [10].

Biological method

This form of remediation is known as bioremediation; it involves the breakdown of contaminants by biological matter into smaller and harmless substances. This process involves both microorganisms and plants to break down organic compounds, and this remediation process is normally governed by factors such as oxygen, temperature, pH, and water activity of the polluted soil that could affect or speed up the remediation process. Bioremediation is a promising technique, and its application is notable due to low cost and high effectiveness [11].

Chemical method

The chemical treatment method is deployed to transform harmful contaminants into less toxic forms [12]. Although it does not always degrade these pollutants into less harmful substances, it normally generates by-products during application. The chemical treatment method is not typically deployed to tackle large amounts of pollutants [13].

Fig. 1. Crude oil spillage as a result of oil theft in the Niger Delta region [14]. (Source: Tantita Security Services Limited-image enhanced with artificial intelligence software ChatGPT).

Bioremediation and Its Applications

Bioremediation is one technique that is basically applied to revive contaminated sites in an environmentally friendly manner at a reduced cost. Scientists have come up with so many methods to this effect, but these conventional methods have their limitations as a result of environmental factors. Indigenous microorganisms play a key role in tackling most of these environmental challenges affecting bioremediation [14]. Bioremediation applications can be divided into *in situ* methods or *ex situ* method; the technique to deploy depends on the nature of the pollutant, the depth and degree of the pollution, the location of the spill, the environment (terrestrial or aquatic), the cost of treatment, and environmental policies. Likewise, in choosing a bioremediation technique, environmental factors such as oxygen, temperature, nutrients, pH, and other abiotic factors are considered. For *ex situ* bioremediation techniques, these are some of the methods used [15].

Biopile

This method involves excavating the soil, which is then amended with nutrients and aerated to enhance microbial activities. This remediation technique is normally applied in temperate regions and helps to reduce the volatilization of pollutants with small molecular weight [16]. In comparison to nanobioremediation, this approach has disadvantages because it requires a lot of area and is expensive to maintain and run [4].

Windrows

This form of treatment involves steady mixing of polluted soil to speed up the bioremediation process. This effect increases the degradation activities of hydrocarbon-degrading microorganisms present in the soil. The Windrow treatment has its limitations; it can develop anoxic conditions, which slow down bioremediation and lead to the emission of greenhouse gases [17].

Land Farming

This is among the simplest methods used; it's cost-effective and does not involve large equipment. For bioremediation to be applied effectively, the contaminated soil must be transported 1.7 meters to the ground surface. In order to improve the remediation process, the contaminated soil is continuously tilled and nutrients are added to encourage natural microorganisms [18,19]. The land farming system can be applied in both tropical and temperate regions and is in line with government regulations [15]. The fabrication of an ideal land farming design with an impermeable thick liner reduces leakage of pollutants into the soil and neighboring areas [20]. This technique is quite simple and normally applied for large volumes of polluted soil [21]. However, it requires a large space and has minimal efficacy in inorganic pollutant removal [5,22].

Bioventing and Biosparging

The bioventing method involves dispatching oxygen to the unsaturated (vadose) zone to increase the activities of autochthonous microorganisms [23,24]. In biosparging, oxygen is injected at the saturated zone (subsurface) to stimulate microbial activities, a technique that depends on soil permeability and pollutant biodegradability [20].

Principles of Nanobioremediation techniques

Traditional methods of decontaminating highly polluted environments take a long period to implement and leave secondary waste behind [25]. The combined effect of nanotechnology with bioremediation could foster significant change in remediation, thereby speeding up the degradation process. Nanobioremediation is a process [5] that involves the use of nanoparticles to remove environmental pollutants such as heavy metals and hydrocarbons. Microorganisms utilize these pollutants as a source of carbon and energy, and this potential can reduce the total cost of cleaning up massively polluted areas within a short period [16].

Synthesis and Characterization

The most common natural nanoparticles are found in soil colloids, which contain minerals such as silicate in clay [26]. Traditional methods of generating nanoparticles involve physical or chemical methods [5]. However, green biological methods using microorganisms and plants are safer and more cost-effective [9,27]. Engineered Green Synthesis of Nanoparticles (EGSON) has gained attention as a sustainable approach [22] (**Fig. 2**).

To obtain comprehensive data, nanoparticles must be characterized using techniques such as:

- X-ray diffraction (XRD): To assess crystallinity and particle size [28].
- Scanning electron microscopy (SEM): To investigate shape and surface morphology [29].
- Transition electron microscopy (TEM): To capture core-shell structure and high-resolution images [12].

Behavior and Combined Impact

Studies on the ecotoxicity of nanoparticles indicate that even at low doses, some (like silver or fullerenes) are harmful to certain bacteria [12]. These pollutants constitute a major threat to marine biodiversity [6,30]. However, the combined method of nanotechnology and bioremediation creates eco-friendly strategies for remediating hazardous pollutants [31]. Numerous studies have evaluated the catalytic properties of various nanoparticles to reduce environmental contaminants [32].

Silica Nanoparticles

In the Niger Delta, plants and agricultural waste have been identified as sources to synthesize nanoparticles [30]. Silica nanoparticles (SiNPs) from engineered green synthesis function as adsorbents due to their large surface area and high selectivity for metal ions. These materials are widely used due to their low toxicity and stability [33].

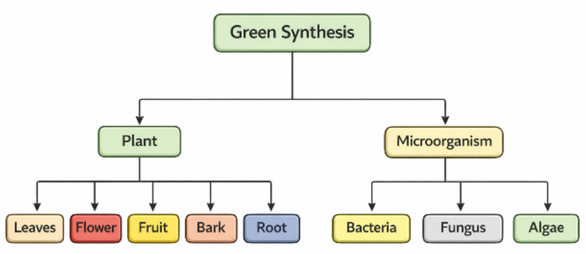

Fig. 2. Green synthesis of nanoparticles from plant and microorganism sources. Source: nanobioremediation: fundamentals and applications [21].

Structure and Properties of Silica Nanoparticles

Generally, there are only three biogenic metal oxides known currently worldwide: Silica oxide, Iron oxide, and Manganese oxide. Silicon (Si) is the second most abundant element on Earth after oxygen; the combination of silicon and oxygen forms silica or silicon dioxide (SiO_2). Silica oxide as a biogenic metal oxide, has caught the attention of scientists all over the world for the development of novel materials by biomimicry. Silica oxide can be found in all five kingdoms (bacteria, fungi, protists, plants, and animals). Mostly, silica nanoparticles are obtained from silicon dioxide, which is commonly found in rocks. They can be synthesized via many methods, such as hydrolysis and chemical vapour deposition. Just like other nanoparticles, silica has a high melting point, can resist chemical attack, and withstand heat, making it an ideal material for structural and industrial purposes [34,35].

Selection of Nanoparticles Synthesised from Different Plants
As noted by Maynard [36], a variety of plants can be used to synthesize specific nanoparticles of varying sizes (**Table 1**):

Table 1. Selected plant species used in green synthesis of metal and metal oxide nanoparticles.

Plants	Nanoparticles	Sizes (nm)
Aloe vera	Au, Ag	50–350
Aloe vera	In_2O_3	5–50
Bambusa vulgaris	Si	18–35
Camellia sinensis	Ag, Au	30–40
Curcuma longa	Pd	10–15
Diospyros kaki	Pt	15–19
Psidium guajava	Ag	25–30

Bamboo Leaves as a Resource for Synthesis
Silica nanoparticles are synthesized and demonstrated to be non-toxic, economical, and environmentally benign. One of the most common trees in the Niger Delta, bamboo (*Bambusa vulgaris*), is frequently used in construction, leaving its leaves as waste. The leaves of a mature bamboo contain over 41% SiO_2. These leaves can be used to create silica nanoparticles via acid precipitation to assess the structure, shape, purity, and yield [37,38].

Ecotoxicity and Health Implications
The introduction of Engineered Green Synthesis of Nanoparticles (EGSON) into the environment has played a significant role in the nanobioremediation of polluted soil; however, most of these nanoparticles can have damaging effects once they enter the environment. In order to prevent such situations, scientists have channeled their research toward the toxic nature of these nanoparticles [39]. The oxidative stress in terms of reactive oxygen species (ROS) generation is one parameter used to measure ecotoxicity, as microbial cells apply protective responses that can be measured as genetic or enzymatic expressions. Nanoparticles like TiO_2, ZnO, and SiO_2 can generate excited electrons when exposed to light, forming superoxide radicals. This exposure can happen intentionally during remediation or as a result of accidental discharge [40]. To ensure safety, some scientists suggest using magnetic nanoparticles, as they can be easily recovered using magnetic traps if leakages occur [41,42].

Ecotoxicity of Metal and Oxide Nanoparticles
The toxicity of metal particles is influenced by binding specificity to biological sites and solubility. Metal nanoparticles exhibit antibacterial activities and exert cytotoxicity as a result of the charge at the membrane surface. Gram-positive cells are less prone to nanotoxic effects due to a thick peptidoglycan layer compared to gram-negative ones [43]. In studies of TiO_2, SiO_2, and ZnO, antibacterial activity was monitored up to concentrations of 5000 mg/L. It was found that *B. subtilis* was the most sensitive to these effects [44]. Magnetic nanoparticles are preferred due to their low toxicity and the fact that they can be recovered easily during the treatment of water [45].

Synthesis and Evaluation Methods

How to Synthesize Silica Nanoparticles from Bamboo Leaves
Bamboo leaves are cleaned, dried, ground into powder, and calcined for four hours at 750°C. The powder is then boiled in sodium hydroxide (NaOH) for two hours, filtered, and titrated against hydrochloric acid (HCl) to produce a white gel. This gel is then calcined and refluxed to obtain the final silica nanoparticles [46]. The functional groups are identified by FTIR, and morphology is determined via SEM. Surface area and pore size are measured using SAA and BJH procedures [47]. The ecotoxicity assay on microorganisms involves preparing nanoparticle stocks in deionized water to determine the Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC) [7,48].

CONCLUSION

Because of their availability, affordability, and safety, silica nanoparticles have recently drawn interest for the bioremediation of petroleum-polluted soil. Future developments in bioremediation applications depend on industrial involvement and a closer examination of the environmental impact, in addition to manufacturing cost, even if the green synthesis of these nanomaterials from readily available plants has only been done on a microscale.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AUTHORS' CONTRIBUTION

C.J and A.O. contributed to conceptualization and design of the study, N.P drafted the manuscript. All authors reviewed and approved the final version for submission.

DATA AVAILABILITY STATEMENT

Data available on request.

AI USAGE DECLARATION

The authors used generative AI for language editing only. The authors take full responsibility for the content.

REFERENCES

1. Agarry SE, Solomon BO. Kinetics of batch microbial degradation of phenols by indigenous Pseudomonas fluorescence. Int. J. Environ. Sci. Technol. 2008;5:223–32. https://doi.org/10.1007/BF03326016
2. Allamin IA, Shukor MY. Phytoremediation of PAHs in Contaminated Soils: A Review. Bioremediation Sci. Technol. Res. 2021;9:1–6. https://doi.org/10.54987/bstr.v9i2.609
3. Kulkarni K, Manujendra Kumar P, Kulkarni A, Satpute S. Bioremediation of hazardous Metanil yellow dye by using Trichoderma and Azotobacter biofertilizers. Acta Ecol. Sin. 2023. https://doi.org/10.1016/j.chnaes.2023.11.007
4. Boelee E, Geerling G, van der Zaan B, Blauw A, Vethaak AD. Water and health: From environmental pressures to integrated responses. Acta Trop. 2019;193:217–26. https://doi.org/10.1016/j.actatropica.2019.03.011
5. Busi S, Rajkumari J. Nanobiotechnology: Applications in environmental remediation. Nanobiotechnology Concepts Appl. 2019
6. Kulkarni N, Muddapur U. Biosynthesis of metal nanoparticles and their applications in environmental remediation. J. Nanotechnol. 2014;2014:1–8. https://doi.org/10.1155/2014/510246
7. Saratale RG, others. A critical review on biomass-based sustainable biorefineries using nanobiocatalysts. Bioresour. Technol. 2022;363:127926. https://doi.org/10.1016/j.biortech.2022.127926

8. Golgeri MDB, others. Microbial naringinase: From microbial source to its current applications in various fields. Biologia (Bratisl.) 2025;80:977–91. https://doi.org/10.1007/s11756-025-01888-6
9. Ezeonu CS, Tagbo R, Anike EN, Oje OA, Onwurah INE. Biotechnological tools for environmental sustainability: Prospects and challenges for environments in Nigeria-a standard review. Biotechnol. Res. Int. 2012;2012:450802. https://doi.org/10.1155/2012/450802
10. Ajayan PM, Schadler LS, Braun PV. Nanocomposite science and technology 2006
11. Alabresm A, Chen YP, Decho AW, Lead J. A novel method for the synergistic remediation of oil-contaminated water using bacteria and silica nanoparticles. Sci. Total Environ. 2018;627:1136–47. https://doi.org/10.1016/j.scitotenv.2018.02.277
12. Koul B, Jack P. Biotechnological strategies for soil remediation 2018. https://doi.org/10.1007/978-981-13-2420-8
13. Kumar R, Roopan SM, Prabhakarn A, Khanna VG, Chakroborty S. Agricultural waste Annona squamosa peel extract: biosynthesis of silver nanoparticles. Spectrochim. Acta. A. Mol. Biomol. Spectrosc. 2012;90:173–6. https://doi.org/10.1016/j.saa.2012.01.029
14. Bhatt P, Pandey SC, Joshi S, Chaudhary P, Pathak VM, Huang Y, et al. Nanobioremediation: A sustainable approach for removal of toxic pollutants from the environment. J. Hazard. Mater. 2022;427:128033. https://doi.org/10.1016/j.jhazmat.2021.128033
15. Besalatpour A, Hajabbasi MA, Khoshgoftarmanesh AH, Dorostkar V. Landfarming process effects on biochemical properties of petroleum-contaminated soils. Soil Sediment Contam. 2011;20:234–48. https://doi.org/10.1080/15320383.2011.546447
16. Dias RL, Ruberto L, Calabró A, Balbo AL, Del Panno MT, Mac Cormack WP. Hydrocarbon removal and bacterial community structure in on-site biostimulated biopile systems designed for bioremediation of diesel-contaminated Antarctic soil. Polar Biol. 2015;38:677–87. https://doi.org/10.1007/s00300-014-1630-7
17. Bottero JY, Rose J, Wiesner MR. Nanotechnologies: tools for sustainability in a new wave of water treatment processes. Integr. Environ. Assess. Manag. 2006;2:391–5. https://doi.org/10.1002/ieam.5630020411
18. Silva-Castro GA, Uad I, Rodríguez-Calvo A, González-López J, Calvo C. Response of autochthonous microbiota of diesel-polluted soils to landfarming treatments. Environ. Res. 2015;137:49–58. https://doi.org/10.1016/j.envres.2014.11.009
19. Volpe A, D'Arpa S, Del Moro G, Rossetti S, Tandoi V, Uricchio VF. Fingerprinting hydrocarbons in a contaminated soil from an Italian natural reserve and assessment of a low-impact bioremediation approach. Water. Air. Soil Pollut. 2012;223:1773–82. https://doi.org/10.1007/s11270-011-0982-7
20. da Silva LJ, others. Technological solutions for treatment of oily sludge. Waste Manag. Res. 2012;30:1016–26. https://doi.org/10.1177/0734242X12448517
21. Maila MP, Colete TE. Review of environmental biotechnology for soil remediation. Rev. Environ. Sci. Biotechnol. 2004;3:349–60. https://doi.org/10.1007/s11157-004-6653-z
22. Singh SK, Singh RK. An overview on remediation technologies for polycyclic aromatic hydrocarbons in contaminated lands: a critical approach. Environ. Dev. Sustain. 2025;27:2753–87
23. Philp JC, Atlas RM. Bioremediation: Applied microbial solutions for real-world environmental cleanup 2005
24. Christopher CA, Chikere CB, Okpokwasili GC. Bioremediation techniques-classification based on site of application: Principles, advantages, limitations and prospects. World J. Microbiol. Biotechnol. 2016;32:180. https://doi.org/10.1007/s11274-016-2137-x
25. Nwogu TP, Christopher A, Ogugbue CJ. Bioremediation of a crude oil polluted agricultural soil at various soil depths. Biotechnol. Res. Int. 2015;2015:657349
26. Edgar SRG, others. A critical review on biomass-based sustainable biorefineries using nanobiocatalysts. Bioresour. Technol. 2022;363:127926. https://doi.org/10.1016/j.biortech.2022.127926
27. Gamallo MLF, Feijoo G. Nano-based technologies for soil remediation. Nanomater. Soil Remediat. 2020. https://doi.org/10.1016/B978-0-12-819355-6.00010-8
28. Harpreet S, Neha B, Shailendra M, Madhu K. Magnetic nanocomposites for oil-spill remediation. Environ. Nanotechnol. Monit. Manag. 2020;14:100305. https://doi.org/10.1016/j.enmm.2020.100305
29. Bolshakova O, Zherebyatieva O, Sarantseva SV. Fullerenes in vivo. Toxicity and protective effects. Nanotoxicology 2025;19:233–58. https://doi.org/10.1080/17435390.2025.2471273
30. Liu Y, Xu K, Cheng J. Different nanomaterials for soil remediation affect avoidance response and toxicity response in earthworm (Eisenia fetida). Bull. Environ. Contam. Toxicol. 2020;104:477–83. https://doi.org/10.1007/s00128-020-02823-y
31. Lu AH, Salabas EL, Schüth F. Magnetic nanoparticles: Synthesis, protection, functionalization, and application. Angew. Chem. Int. Ed. 2007;46:1222–44. https://doi.org/10.1002/anie.200602866
32. Lyon DY, Thill A, Rose J, Alvarez PJJ, Wiesner MR, Bottero JY. Ecotoxicological impacts of nanomaterials. Environ. Nanotechnol. Appl. Impacts Nanomater. 2007:445–79
33. Liu Z, Shi S, Li YL, Liu H, Liu J. Advances and Challenges in Rhenium Recovery from Copper Smelting Dirty Acid: Solvent Extraction, Ion Exchange, and Adsorption. J. Sustain. Metall. 2025:1–9. https://doi.org/10.1007/s40831-025-01251-8
34. Makarov VV, Love AJ, Sinitsyna OV, Makarova SS, Yaminsky TV, Taliansky ME, et al. "Green nanotechnologies": Synthesis of metal nanoparticles using plants. Acta Naturae 2014;6:35–44. https://doi.org/10.32607/20758251-2014-6-1-35-44
35. Masindi V, Muedi KL. Environmental contamination by heavy metals. Heavy Met. 2018. https://doi.org/10.5772/intechopen.76082
36. Maynard AD. Nanotechnology and occupational health: New technologies-new challenges. Ann. Occup. Hyg. 2007;51:1–12. https://doi.org/10.1007/978-1-4020-5859-2_1
37. Medyak GV, others. Synthesis of silica nanoparticles from vegetable waste. Russ. J. Appl. Chem. 2001;74:1658–63. https://doi.org/10.1023/A:1014849001051
38. Mounir L, others. Characterization of silica nanoparticles synthesized from bamboo leaves. Procedia Eng. 2011;4:148–54
39. Nikolopoulou M, others. Marine oil spill bioremediation: A review of environmental factors and constraints. Mar. Pollut. Bull. 2017;77:37–44. https://doi.org/10.1016/j.marpolbul.2013.10.038
40. Abbott LC, Maynard AD. Exposure assessment approaches for engineered nanomaterials. Risk Anal. 2010;30:1634–44. https://doi.org/10.1111/j.1539-6924.2010.01446.x
41. Daroczi B, Kari G, Houchen NW, Dicker AP. In vivo radioprotection by the fullerene nanoparticle DF-1 as assessed in a zebrafish model. Clin. Cancer Res. 2006;12:6527–33. https://doi.org/10.1158/1078-0432.CCR-06-0514
42. Qiao K, Tian W, Bai J, others. Application of magnetic adsorbents based on iron oxide nanoparticles for oil spill remediation: A review. J. Taiwan Inst. Chem. Eng. 2019;97:227–36. https://doi.org/10.1016/j.jtice.2019.01.029
43. Parada J, Rubilar O, Fernández-Baldo MA, Bertolino FA, Durán N, Seabra AB, et al. The nanotechnology among US: are metal and metal oxides nanoparticles a nano or mega risk for soil microbial communities? Crit. Rev. Biotechnol. 2019;39:157–72. https://doi.org/10.1080/07388551.2018.1523865
44. Adams LK, Lyon DY, Alvarez PJJ. Comparative ecotoxicity of engineered nanoparticles in water. Water Res. 2006;40:3527–32. https://doi.org/10.1016/j.watres.2006.08.004
45. Paudyn K, others. Field and laboratory studies of the biodegradation of diesel fuel in Antarctic soils. Cold Reg. Sci. Technol. 2008;53:102–14. https://doi.org/10.1016/j.coldregions.2007.07.006
46. Rajput VD, Singh A, Singh VK, Minkina TM, Sushkova S. Impact of nanoparticles on soil resources. Nanomater. Soil Remediat. 2021:65–85. https://doi.org/10.1016/B978-0-12-822891-3.00004-9
47. Rasheed T, Ahmad N, Ali J, Hassan AA, Sher F, Rizwan K, et al. Nano- and micro-architecture cues as smart materials to mitigate recalcitrant pharmaceutical pollutants from wastewater. Chemosphere 2021;274:129785. https://doi.org/10.1016/j.chemosphere.2021.129785
48. Shah M, Fawcett D, Sharma S, Tripathy S, Poinern G. Green synthesis of metallic nanoparticles via biological entities. Materials 2015;8:7278–308. https://doi.org/10.3390/ma8115377