Review Paper:

Advances in Nanotechnology for Aquatic, Atmospheric Pollution Control: A Review

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Abstract

This review aims to elucidate the breakthroughs in nanotechnology applications in eliminating pollution in the environment. Thus, one cannot underestimate the transformative power of nanotechnology in addressing the issues of contamination in the air, water and soil. Present review entails different nanomaterials such as nanoparticles, nanocomposites and nanofibers with special emphasis on their use in remediating pollutant. The findings of current study established that the efficiency and effectiveness of nanotechnology enhanced solutions outweigh the conventional techniques in the elimination of pollutants and other anthropogenic activities like oil spills.

Nano-catalysts have a very high potential in controlling the air pollution. Nano-filters also reveal high effectiveness in air filtration, nano-absorbents and nanomembranes are used in water purification and desalination. Magnetic nanomaterials and nano absorbents are used for effective removal of oils spills.

Keywords: Nanotechnology, pollution control, contamination.

Introduction

Pollution has remained a complex issue affecting the environment, organisms and man's existence in the world. Due to the increased level of industrialization and urbanization over the past decades, pollutants that are being released into the environment are of great concern to scientist's policy makers and the society. Realization of the consequences of pollution and the subsequent attempts to address this menace have culminated in a search for new alternatives and one of the approaches eyed for exploitation is nanotechnology[13,33]. The theme of the problem is represented in the figure 1.

Background of Environmental Pollution Problems: Pollutants which range from air, water and contaminated soil have led to poor environmental quality and have become a major concern across the globe. Human activities including industries, transportation and other farming activities, spread out pollutants like heavy metals, organic compounds as well as particulate matters which affect air and water quality, the soil and the ecological systems. These pollutants are known to affect human well-being through respiratory illnesses, cancer, neurological disorders[28,34]. Classification of atmospheric and aquatic pollutions is depicted in the figure 2.

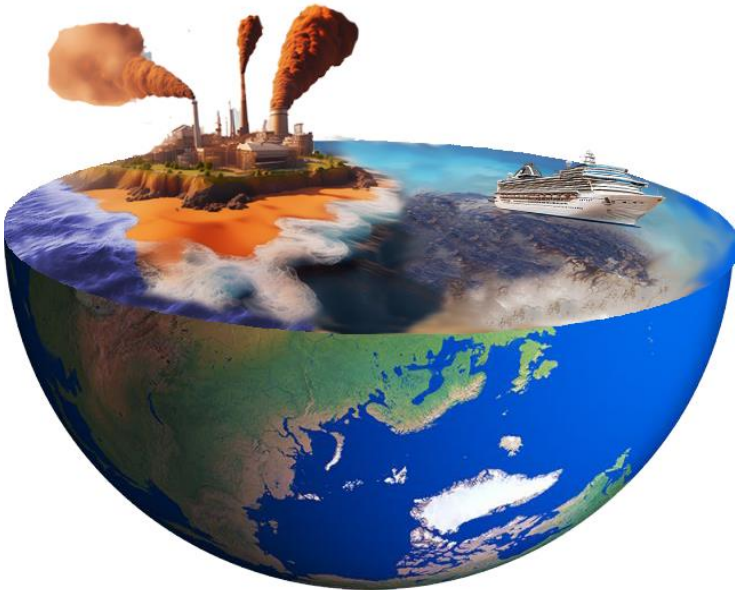

Figure 1: Graphical Abstract of the theme

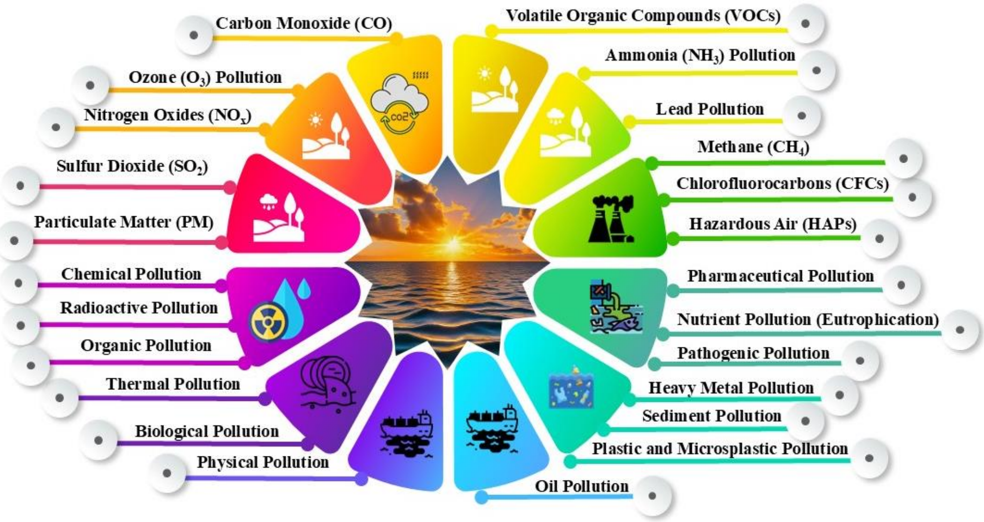

Figure 2: Different types of aquatic and environmental pollutions

Importance of nanotechnology in pollution reduction: Nanotechnology is an important tool to protect the environment and ecosystems from various types of pollutions (like air, water, oil spills). It guarantees that pollutants are significantly reduced from the required system[8]. Nanotechnological applications provide special prospects for confronting environmental pollution problems. Some of the specific characteristics of nanomaterials include: large surface area to volume ration, increased chemical activity and variable surface chemistry making them ideal tools for pollution control. Titanium dioxide (TiO_2), iron oxides, carbon nanotubes and graphene-based materials are the most frequently investigated nanoparticles for their ability to remove pollutants, as well as for their degradation features[11,27,37].

In pollution control, nanotechnology can go with an alien methodology like photocatalysis with the nanomaterial to hasten the rate of breakdown of pollutants especially on exposure to light. For instance, TiO_2 nanoparticles have been applied in photocatalysis to destruct the materials like organic chemicals/toxins that are found in wastewaters and emissions. Moreover, in adsorption, the nanomaterials are used in the removal of pollutants whereby using big surface areas and reactivity of adsorbents. Also, use of nanoscale sensors and detection systems assist in the continuous assessment of the concentration of pollutants in the immediate environment[1,9,20]. This review aims to provide a comprehensive summary of current advances and achievements in the field of nano-scale materials to combat environmental pollution.

Overview of Nanotechnology

Nanotechnology is the design of functional substances, devices and systems by applying the principles of material engineering to physical matter at the molecular level. The nanomaterials are used in nanotechnology to achieve the goals which are engineered at the nanoscale in the forms of nanoparticles, nanotubes, nanowires, nanocomposites and nanostructured surfaces. They exhibit unique properties due to quantum confinement and surface effects. These materials are fabricated into two major classified approaches. Top-down methods involve the reduction of larger structures to nanoscale dimensions, such as lithography and etching. Bottom-up methods build structures atom by atom or molecule by molecule, like self-assembly and molecular beam epitaxy.

Preparation of nanoparticles is usually through chemical techniques. In case of chemical preparation various methods exist which include solution combustion[16], sol-gel, electrochemical, colloidal, capping etc.[18,30] Out of all these techniques, the solid-state reaction technique is perhaps the most preferred in the synthesis of nanoscale poly crystalline solid materials from a mix of starting reagents[25]. The techniques such as solid-state reaction, chemical combustion, sol-get, ball milling etc. are widely used techniques for synthesizing the nanomaterials[26].

Prepared materials are generally characterized by the Scanning electron microscopy (SEM), Transmission electron microscopy (TEM), X-ray diffraction (XRD), FTIR, DRS and spectroscopic methods which are essential for characterizing nanomaterials and understanding their structure-property relationships[3,17,21,31]. Various types of nanomaterials are employed in environmental applications, each offering unique advantages. These are nanoparticles, nanocomposites, nanofibers, carbon nanomaterials, nanoporous materials.

Nanotechnological Methods for Air Pollution Control: Nanomaterials offer promising solutions for air purification by efficiently capturing and degrading pollutants such as volatile organic compounds (VOCs), particulate matter (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x) and other harmful gases. These nanomaterials leverage their high surface area, tailored surface chemistry and unique physicochemical properties to enhance pollutant adsorption, catalytic conversion and filtration efficiency[18,19]. Most commonly used nanomaterial compounds are for air purification:

Metal-Organic Frameworks (MOFs): MOFs are highly porous materials with tunable structures and large surface areas, making them effective for gas adsorption and storage. They can be functionalized to selectively capture specific pollutants, such as NO_x and VOCs, through physisorption or chemisorption mechanisms. Mostly used compounds are zirconium based MOFs (UiO-66), aluminum based MOFs (MIL-100) and copper-based MOFs (HKUST-1). MOFs are not only used for adsorbent materials for indoor and outdoor air purification, but also for catalytic converters, gas sensors[5,38].

Nanoporous Silica Materials: Nanoporous silica materials have well-defined pore structures and high surface areas, enabling efficient adsorption of gasses and vapors. Surface functionalization with specific chemical groups enhances pollutant selectivity and catalytic activity. Mostly used mesoporous silica nanoparticles (MSN), zeolites and silica aerogels, nanoporous silica materials are good air filters[15,24].

Metal Oxide Nanoparticles: Metal oxide nanoparticles exhibit photocatalytic activity under UV or visible light irradiation, leading to the decomposition of pollutants into harmless byproducts such as water and carbon dioxide. They can also adsorb gases and VOCs through surface interactions. Frequently used are: titanium dioxide (TiO_2), zinc oxide (ZnO), cerium oxide (CeO_2) and ferrous oxide. Table 1 shows main class of nanomaterials, their respective properties and targeted pollutants.

Nanotechnological Solutions for Water Pollution Control: Nanotechnological solutions offer unprecedented opportunities for addressing water pollution challenges by providing innovative approaches for pollutant removal, remediation and monitoring. Engineered nanomaterials such as metal oxides, carbon nanotubes and nanocomposites, exhibit unique physicochemical properties, including high surface area, reactivity and selectivity, making them highly effective for capturing, degrading and immobilizing contaminants in water sources. Advanced nanofiltration membranes, based on thin-film nanocomposites and self-assembled nanomaterials, enable precise control over pore size, flux and rejection properties, facilitating efficient removal of pathogens, heavy metals and organic pollutants. Nano catalysts including noble metals and metal oxides, catalyze oxidation, reduction and hydrolysis reactions to decompose organic pollutants and neutralize toxic compounds, enhancing water quality and ecosystem health.

Furthermore, nano sensors and nano-enabled analytical techniques enable real-time monitoring of water quality parameters, such as pH, conductivity and pollutant concentrations, enabling timely detection and response to pollution incidents. Overall, nanotechnological solutions hold immense promise for revolutionizing water pollution control strategies, offering sustainable, cost-effective and scalable approaches to safeguarding freshwater resources for present and future generations[10].

Nanomaterials for water purification: Nanomaterials are regarded as novel reagents in the water purification processes and their efficiency could hardly be compared to other reagents and materials. Nanoparticles, nanocomposites and nanofibers are some of the engineered nanomaterials distinguished by traits like elevated surface area to volume ratio, reversible surface chemistries and selectivity in adsorption of different pollutant species and are efficient in the purification of different water sources.

Some nanomaterials can selectively bind to specific pollutants; its mechanisms imply interaction with the pollutants and functional groups attached to the nanomaterials surface to remove the pollutants like heavy metals, organic pollutants and pathogens. Also, modern nanofiltration membranes with nano inclusions allow better control of the pore size, allowing a high degree of removal of pollutants and high permeability rates.

Similarly, the nano catalysts help in performing catalytic degradation of organic pollutant materials which in turn are environmentally friendly and efficient methods of water treatment. Realizing the potential of nanotechnology for water purification opens up the possibility of providing required fresh and clean water to the people around the world who were affected by water scarcity and contamination issues[35].

Titanium dioxide, zinc oxide and iron oxide etc. are known photocatalytic materials that can break the organic chemical and kill bacteria and virus irradiation by UV or visible light. These nanoparticles can be used to remove pollutants such as dyes, pesticides and bacteria from the water source. Carbon nanotubes (CNTs), graphene and activated carbon are frequently employed materials for water purification due to large surface area and adsorption ability.

Table 1
Nanomaterials Used in Air Pollution Control Technologies

Nanomaterials	Pollutant Target	Application	Efficiency
Carbon Nanotube	VOCs, CO_2, NO_x	Filtration, Adsorption	High[36]
TiO_2 Nanoparticles	NO_x, SO_x	Photocatalysis	Moderate[9,14]
Graphene Oxide	PM2.5, Heavy Metals	Adsorption, Sensing	High[2]

CNTs and graphene can filter heavy metals, organic pollutants and microorganisms from water and activated carbon can adsorb organic compounds, odors and chlorine. Nanocomposite refers to at least two types of nanomaterial integrated in a single material in order to improve the efficiency of water purification. While metal oxide nanoparticles may be synthesized with carbon nanotubes or graphene, it will further enhance photocatalytic activity and adsorption capacity, enhancing the removal of contaminants[4].

Nanofibers and membranes made from polymers for example are applied in filtration and separation in drinking water treatment. These materials can filter out solids, microbes and viruses from the water and also can have designated chemical functionalities to adsorb particular pollutants. Silver nanoparticles have been known to have antibacterial characteristics that can be used in water purification to kill bacteria and viruses. These attributes make it possible for silver nanoparticles to be incorporated in filters, membranes, or coating to eliminate biofouling. Zeolite nanoparticles are characterized with micropores that allow the particles to selectively capture ions, heavy metals and organic compounds in water. These nanoparticles are widely used in water softening treatment, ion exchange treatment and wastewater or effluent treatment. These nanomaterials are essentially used in water purification technologies where they are fundamental in solving water problems and providing safe and clean water for drinking[32].

Frontiers of Nanotechnology in Oil Spill Pollution: A new approach to combat oil spill pollution is presented by nanotechnology as it creates specific and effective material and methods for combating pollution and cleaning up oil-contaminated territories. It was disclosed in the studies that ferrite-based nanomaterials such as iron oxide (Fe_3O_4) nanoparticles and copper-based ferrites possess a high richness in the characterization of magnetism, surface area and adsorption competence[22].

Iron Oxide and Cupper ferrite Nanoparticles: Magnetic or ferrite nanoparticles also known as iron oxide and cupper-based iron oxide nanoparticles possess superparamagnetic property because of which these particles can be easily collected through an external magnetic field. This property ensures that oil spills can be rendered from the surface of water by dispersing the nanoparticles and then collecting them through magnetism. Iron oxide nanoparticles also have inherent hydrophobic nature which helps these nanoparticles to adhere to oil molecules preferentially on their surface[7,22,29]. Table 2 indicates the different classes of nanomaterials and its function in oil spill remediation mechanism and properties.

The stability, dispersibility and adsorption ability of iron oxide nanoparticles for oil can be enhanced through functionalization/surface modification. Molecules such as hydrophilic or amphiphilic are incorporated with the surface of the nanoparticles to increase the affinity of the nanoparticles with water and oil phases, which facilitate the separation and cleanup process.

Copper-based ferrites and oxides: Copper based ferrite nanoparticles are made-up of metal ions including Cu^{2+} and Fe_3O_4 or other TMOs and have potential in the remediation of the oil spills due to its magnetic and adsorptive characteristics. These materials involve the magnetic response of the ferrite nanoparticles, the catalytic activity of copper and hydrophobicity, necessary to improve the efficiency in removing the spilled oil. CuO is one of the oxide nanoparticles that has a great tendency to adsorb the organic compounds such as the hydrocarbons found in crude oil. The photocatalytic properties of copper oxide nanoparticles assist the oxidation of oil components with the help of which larger HC molecules are broken down into less hazardous components.

Functionalized copper-based nanomaterials can enhance to activate individual components of the oil through a functionalization profile so that it enhances treatments for oil spills. There are probable changes on the surface of nanoparticles that involve ligands or functional groups that improve the dispersibility, stability and reactivity of nanoparticles in aqueous systems and hence, make them useful in oil spill response operations[6,36].

Among the analyzed materials, the nanomaterials based on ferrites showed good results due to the versatility of their applications related to oil spill pollution, the magnetic recovery technique, adsorption features and the catalytic degradation of pollutants, using iron oxide nanoparticles and copper-based ferrites and oxides. Future investigations in the area of nanotechnology have the potential to enhance the understanding and application of techniques in dealing with oil spill occurrence, thus, reducing the effects of oil content on the aquatic life and shorelines of regions affected.

Table 2
Nanomaterials for Oil Spil Remediation

Nanomaterial	Oil Type	Mechanism	Efficiency
Magnetic Nanoparticles	Crude Oil	Magnetic Separation	High[1,23]
Silica-Based Nanocomposites	Diesel, Gasoline	Adsorption	Moderate[12]
Carbon Nanofibers	Various Hydrocarbons	Adsorption and catalysis	High[23]

Conclusion

Nanotechnology has completely altered the approach to environmental pollution by providing new technologies for the control and disposal of pollutants. It has been successfully applied to gaseous, liquid and marine pollution while also promoting the efficiency of resource usage. Nevertheless, production scale up, cost reduction and compliance with environmental controls still pose challenges. In this scenario, copper and iron-based host materials emerge as viable solutions for dealing with oil spills, thus helping to preserve the environment for future generations.

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References

1. Abdullah M.M.S. and Al-Lohedan H.A., Facile fabrication of magnetite nanoparticles with new hydrophobic amides and their application in oil spill remediation, *Environmental Science and Pollution Research*, **31**, 36986-36994 **(2024)**

2. Anegbe B., Ifijen I.H., Maliki M., Uwidia I.E. and Aigbodion A.I., Graphene oxide synthesis and applications in emerging contaminant removal: a comprehensive review, *Environmental Sciences Europe*, **36**, 15 **(2024)**

3. Basha S.J., Khidhirbrahmendra V., Madhavi J., Thampy U.S.U., Reddy C.V. and Ravikumar R.V.S.S.N., Structural, optical, magnetic and thermal investigations on Cr^{3+} ions doped ZnS nanocrystals by co-precipitation method, *Journal of Science: Advanced Materials and Devices*, **4 (2)**, 260-266 **(2019)**

4. Bharti, Jangwan J.S., Kumar S.S., Kumar V., Kumar A. and Kumar D., A review on the capability of zinc oxide and iron oxides nanomaterials, as a water decontaminating agent: adsorption and photocatalysis, *Applied Water Science*, **12**, 46 **(2022)**

5. Bian Y., Niu Z., Zhang C., Pan Y., Wang Y. and Chen C., Encrusting MOF nanoparticles onto nanofibers via spray-initiated synthesis to boost the filtration performances of nanofiber membranes, *Separation and Purification Technology*, **331**, 125569 **(2024)**

6. Bonthula S., Bonthula S.R., Pothu R., Srivastava R.K., Boddula R., Radwan A.B. and Al-Qahtani N., Recent Advances in Copper-Based Materials for Sustainable Environmental Applications, *Sustainable Chemistry*, **4(3)**, 246-271 **(2023)**

7. Chaudhari D.S., Upadhyay R.P., Shinde G.Y., Gawande M.B., Filip J., Varma R.S. and Zbořil R., A review on sustainable iron oxide nanoparticles: syntheses and applications in organic catalysis and environmental remediation, *Green Chemistry*, **26(13)**, 7579-7655 **(2024)**

8. Das D., Chakraborty D. and Barman S., Emerging Role of Nanotechnology-Based Devices for Detection of Environmental Contaminants, *Functionalized Smart Nanomaterials for point-of-Care Testing*, 199-209, https://doi.org/10.1007/978-981-99-5787-3_11 **(2023)**

9. Halim W., Eddahbi A., Mouna S.I., Kassiba A. and Ouaskit S., Synthesis of perfect TiO_2 nanospheres decorated by silver shell nanoparticles for photocatalytic applications, *Journal of Cluster Science*, https://doi.org/10.1007/s10876-024-02614-z **(2024)**

10. Hassan S.W.M. and El-Bestawy E.A., Wastewater Treatment Using Nanotechnology and Microorganisms-Assisted Nanotechnology, Proceedings of the National Academy of Sciences, India Section B; Biological Sciences, https://doi.org/10.1007/s40011-024-01632-1 **(2024)**

11. Huang X., Auffan M., Eckelman M.J., Elimelech M., Kim J.H., Rose J., Zuo K., Li Q. and Alvarez P.J.J., Trends, risks and opportunities in environmental nanotechnology, *Nature Reviews Earth & Environment*, **5**, 572-587 **(2024)**

12. Iftekhar S., Deb A., Heidari G., Sillanpää M., Lehto V.P., Doshi B., Hosseinzadeh M. and Zare E.N., Environmental Science and Pollution Research, A review on the effectiveness of nanocomposites for the treatment and recovery of oil spill, *Environmental Science and Pollution Research*, **30**, 16947-16983 **(2023)**

13. Li P., Wang X., Su M., Zou X., Duan L. and Zhang H., Characteristics of Plastic Pollution in the Environment: A Review, *Bulletin of Environmental Contamination and Toxicology*, **107**, 577-584 **(2021)**

14. Manjunathan J., Revathi M., Sowmya H., Meenambiga S.S., Sudha R., Prakash B., Nangan S., Gnanasekaran L. and Thirumalaivasan N., Clean Technologies and Environmental Policy, Recent Advancements in nanotechnological approaches for pollution monitoring and environmental sustainability, *Clean Technologies and Environmental Policy*, https://doi.org/10.1007/s10098-023-02676-z **(2023)**

15. Mohammed R.H., Rashad E., Huo R., Su M. and Chow L.C., Pore-size engineered nanoporous silica for efficient adsorption cooling and desalination cycle, *NPJ Clean Water*, **4**, 38 **(2021)**

16. Munimasthani Sk., Sarathkumar S., Reddy N.B., Zyryanov G.V. and Ravikumar R.V.S.S.N., Luminescence studies on Pr^{3+} & Yb^{3+} doped cadmium calcium pyrophosphate nanophosphors, AIP Conference Proceedings, **2280(1)**, 040034 **(2020)**

17. Munimasthani Sk., Sarathkumar S., Udaychandran Thampy U.S. and Ravikumar R.V.S.S.N., Structural and luminescence studies of Dy^{3+} activated cadmium calcium pyrophosphate, *Applied Physics A*, **126**, 2 **(2020)**

18. Osman A.I., Zhang Y., Farghali M., Rashwan A.K., Eltaweil A.S., Abd El-Monaem E.M., Mohamed I.M.A., Badr M.M., Ihara I., Rooney D.W. and Yap P.S., Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural and food applications: A review, *Environmental Chemistry Letters*, **22**, 841-887 **(2024)**

19. Ouda M., Banat F., Hasan S.W. and Karanikolos G.N., Recent advances on nanotechnology-driven strategies for remediation of microplastics and nanoplastics from aqueous environments, *Journal of Water Process Engineering*, **52**, 103543 **(2023)**

20. Pandey S. and Saxena M., Carbon Nanomaterial for Oil Spill Clean-Up, *Carbon-Based Nanomaterials*, 321-336 https://doi.org/10.1007/978-981-97-0240-4 15 **(2024)**

21. Pradeepa V.M., Kesavan K., Sarathkumar S. and Mohanavel B., Coating temperature in CVD technique effects the CZTS thin film characteristics, AIP Conference Proceedings, **2901**, 040032 **(2023)**

22. Qiao K., Tian W., Bai J., Wang L., Zhao J., Du Z. and Gong X., Application of magnetic adsorbents based on iron oxide nanoparticles for oil spill remediation: A review, *Journal of the Taiwan Institute of Chemical Engineers*, **97**, 227-236 **(2019)**

23. Saharan Y., Singh J., Goyat R., Umar A., Ibrahim A.A., Akbar S. and Baskoutas S., Recent Advances in Soil Cleanup Technologies for Oil Spills: a Systematic Review, *Water, Air & Soil Pollution*, **234**, 503 **(2023)**

24. Saleem H., Zaidi S.J., Ismail A.F. and Goh P.S., Advances of nanomaterials for air pollution remediation and their impacts on the environment, *Chemosphere*, **287**, 132083 **(2022)**

25. Sarathkumar S., Munimasthani Sk., Thampy U.S.U., Madhavi J. and Ravikumar R.V.S.S.N., Synthesis and structural characterization of samarium doped calcium zinc phosphate nanophosphors, AIP Conference Proceedings, **1992**, 030013 **(2018)**

26. Sarathkumar S., Munimasthani Sk., Thampy U.S.U. and Ravikumar R.V.S.S.N., Structural and luminescent properites of $CaZn_2(PO_4)_2$: RE^{3+} (RE = Er and Pr) nanophosphors for versatile device applications, *Journal of Materials Science: Materials in Electronics*, **31**, 11589-11598 **(2020)**

27. Saoud K.M., Nanotechnology for Pollution Reduction, *Qatar Foundation Annual Research Forum*, https://doi.org/10.5339/qfartf.2011.EV08 **(2011)**

28. Sharma A.K., Sharma M., Sharma A.K., Sharma M. and Sharma M., Mapping the impact of environmental pollutants on human health and environment: A systematic review and meta-analysis, *Journal of Geochemical Exploration*, **255**, https://doi.org/10.1016/j.gexplo.2023.107325 **(2023)**

29. Sreekala G., Beevi A.F., Resmi R. and Beena B., Removal of lead (II) ions from water using copper ferrite nanoparticles synthesized by green method, Materials Today: Proceedings, **45(4)**, 3986-3990 **(2021)**

30. Srinivasan L.V. and Rana S.S., A critical review of various synthesis methods of nanoparticles and their applications in biomedical, regenerative medicine, food packing and environment, *Discover Applied Sciences*, **6**, 371 **(2024)**

31. Sundaranayagi S., Sirajunnisa A., Sarathkumar S. and Munimasthani Sk., Analysis bioenergy transformation of press mud through anaerobic digestion by iron oxide nanoparticles, *Rasāyan Journal of Chemistry*, **16(3)**, 1184-1190 **(2023)**

32. Tlili I. and Alkanhal T.A., Nanotechnology for water purification: electrospun nanofibrous membrane in water and wastewater treatment, *Journal of Water Reuse and Desalination*, **9(3)**, 232-248 **(2019)**

33. Trevors J., Water, Air and Soil Pollution, *Water, Air and Soil Pollution*, **205**, https://doi.org/10.1007/s11270-009-0283-6 **(2010)**

34. Trevors J.T., What is a Global Environmental Pollution Problem?, *Water, Air and Soil Pollution*, **210**, 1-2 **(2010)**

35. Vo T.S., Lwin K.M. and Kim K., Recent developments of nano-enhanced composite membranes designed for water/wastewater purification-a review, *Advanced Composites and Hybrid Materials*, **7**, 127 **(2024)**

36. Wang L., Zhu F., Liu E., Yang Y., Yu Q., He Y., Peng W., Lam S.S. and Chen X., Progress in advanced carbon nanotubes composites for air purification, *Advanced Composites and Hybrid Materials*, **7(100)**, https://doi.org/10.1007/s42114-024-00904-8 **(2024)**

37. Wibowo Y.G., Ramadan B.S., Taher T. and Khairurrijal K., Advancements of Nanotechnology and Nanomaterials in Environmental and Human Protection for Combatting the COVID-19 During and Post-pandemic Era: A Comprehensive Scientific Review, *Biomedical Materials & Devices*, **2**, 34-57 **(2024)**

38. Zhang Y., Yuan S., Feng X., Li H., Zhou J. and Wang B., Preparation of Nanofibrous Metal-Organic Framework Filters for Efficient Air Pollution Control, *Journal of the American Chemical Society*, **138(18)**, https://pubs.acs.org/doi/10.1021/jacs.6b02553 **(2016)**.

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