Novel Environmental Remediation Techniques for Enhancing Public Health and Ecosystem Resilience

ABSTRACT

Aim: To address novel environmental remediation techniques for enhancing public health and ecosystem resilience.

Problem Statement: Anthropogenic activities such as deforestation, unplanned urbanization, unsafe agricultural practices and use of wasteful energy reservoirs together with population explosion and rapid industrialization have caused serious environmental pollution affecting public health and disrupting the ecosystem. Identified Prominent pollutantscausing environmental worries have also been identified.

Significance of Study: The cleaning-up of hazardous contaminants using novel environmental remediation techniques to enhance public health and ecosystem resilience is imperative.

Methodology: Previous journals, literatures and other relevant materials which address environmental remediation techniques for contaminants removal were consulted.

Discussion: This review article addresses novel remediation methods for handling new contaminants together with innovative technological means in cleaning environment to achieve ecosystem resilience and enhance public health. Heavy metals, microplastics,pharmaceuticals and industrial chemicals are the prominent emerging contaminants intimidating environmental qualityand public health. There is need to take proactive steps to minimize the concentrations of these toxins which remain adamant in air, soil and water. Novel environmental remediation techniques for pollutants removal to enhance public health and ecosystem resilience are bioremediation, advanced oxidation processes, nanotechnology and using biomimetic materials and coatings.

Conclusion: It is vital to give supremacy to remediation initiatives to ascertain ecological justice. Overcoming pollution problem in order to restore ecological quality and build more resilient and healthier environment is achievable using novel environmental remediation techniques.

Keywords: Public Health, Ecosystem Resilience, Remediation Techniques, Environmental Quality, Pollutants

1. INTRODUCTION

Anthropogenic activities have negatively impacted the Earth resulting from the 21^{st} century industrial revolution. These advancements have caused exceptionalpollution via the speedy development of agrochemicals,electronics, pharmaceuticals and biotech industries which have positively enhanced the agricultural system, healthcare services and advanced technological innovations [1]. The evolution and propagation ofnew and emerging pollutants (NEPs) is presently a major severe challenge. Common NEPs in circulation include antidepressants,microbeads,antibiotics,microplastics, specialty chemicals and so on. Complex behaviors can be exhibited with long-term health and ecological impacts by the xenobiotic compounds which have the potential to persist for longer period in the environment. The accorded dangers linked with NEPs have been on the increase and well-recognized by the global community and thus, there is need for sustainable remediation strategies for urgent action [2].

In the past few decades, environmental pollution has been onthe increaseemanating fromimproved human activities such as unsafe agriculturalpractices,deforestation,population explosion,rapid industrialization, unplanned urbanization andwasteful energy reservoirs utilization and some other anthropogenic activities. Heavy metals,herbicides,chemical fertilizer,pesticides,insecticides, nuclear wastes, greenhouse gases and hydrocarbons are the most prominent pollutants having extreme public and environmentalhealth worries as a result of their high toxicities [3]. Many hazardouswaste sites have been recognized and assessed with more anticipation in decades ahead. Pollutants dischargeinto the environment originates from unlawfuldumping by chemical industries and companies. Many of the adopted techniques used in cleaning up of site in the past were temporary remediation and also expensive. The most common involves excavating the contaminated soil and its hauling away into land filled for incineration. The recent adopted techniques such as soil venting and vapor extraction are not costly but are characterized with partial solution [4].

Environmental remediation is vital for reinstating and conservingour planet's ecosystems. Present centuries of agricultural intensification rapid urbanization and industrializationhave resulted into increased soil, water and air pollution. These are causing serious threats to natural systems, public health and biodiversity. Cross-disciplinary remedies are needed as a result of the complexity and level of the environmental pollution. Traditionally,pollution alleviation plans have targeted pesticides,heavy metals, and industrial chemicals. However, the emergency need for innovative techniques in tackling the environmental pollution challenges has been undermined via the discovery of new contaminants such as microplastics, pharmaceuticals and polyfluoroalkyl materials. Evolving contaminants are the principal worries regarding environmental cleanup as a result of their varied bioaccumulationpotential, persistence and chemical compositions. The sources of the pollutants have been linked to agricultural runoff, personal care products,industrial processes and pharmaceuticals [5]. Potential remediation techniques have been put in place by present environmental science and technology advances in tackling new contaminants. Figure represents the environmental impacts of emerging pollutants which include degradation of water quality, biodiversity loss, air pollution, soil contamination, and disruption of ecosystem.

Figure 1: Environmental Impacts of Emerging Pollutants

The cleaning-up of hazardous contaminants which involves their treatment, removal and containment from environmental media such as sediment, groundwater and soil is referred to as environmental remediation.Before the advancement of land regeneration projects, remediation may be needed by regulations. Incentives may be given to developers, who decide to intentionally cleanup, under municipal or state programs. Some cases of cleanup have been reported in some advanced countries [6]. Typical example is that of New York State's Brownfield Cleanup Program.The waste materials are basically conveyed off-site for dumping into another location if remediation is executed via removal. Physical blockades such as slurry walls can be used in the containment of the waste materials. In the construction industry, the utilization of slurry walls is well-organized. In San Francisco and other earthquake regions, mixed results have achieved in field tests in creating barriers via the adoption of (low) pressure grouting applied in mitigating soil liquefaction risks. Remedial task is mostlyinfluenced by an array of regulatory requests, and may also be a function ofecological risks and human health assessments where no judicial standards exist [7].

Regulation,technical innovation, politics and public participation are essential in environmental remediation. Effective cleaning techniques involve national, local and global collaboration between academia,governments, civil society and industry. The concepts of circular economy and sustainability are vital in solving the principal causes of pollution which needconsumption, systemic production and waste management modifications. A wide and positive technique towards remediation should be taken due to the serious threats posed by environmental contamination [8]. A healthier, cleaner and more resilient Earth can be created for the coming generations using the novel creative collaborations, technology advances and recent scientific knowledge. The principal focus of environmental science and engineering is remediation of contaminated water and soil because of the high impacts of contaminants on human health and ecosystems. The bioaccumulation, mobility and persistence attributes of the emerging contaminants alongside microplastics,medicines,personal care items and industrial chemicals have made them to be very difficult to manage. New contaminants in water and soil systems have stimulatedworries regarding our ecosystems and natural resourcessustainability. These toxins naturallybye-pass standard management and endanger animals, aquatic life and humans. Thus, novel environmental remediation techniquesare required to clean up contaminated areas and keep the environment safe [9].

Another prominent source of environmental pollution is oil spillage which is an incident that usually happen as a result of leaks from storage tanks and pipelines, oil tankersaccidents, oilfield blowouts, oil well waxing,and malfunctioning ofpetroleum manufacturing and refinery equipment. It is imperative for huge spills to be cleaned up and recycled. However, on occasional basis, it is difficult to revive the materials back and thus they remain in the impacted zone and pose environmental threats continuously. There is often pollution risk when collaborated with inability to maintain settings contaminated by oilwhenever oil is extracted. This is peculiar in unusual and harsh locations such as marshes, polar regions, deep sea areas anddeserts [10]. The ecology that generates oil has had an awful time in handling this catastrophe. The availability of hazardous substances such as heavy metals, hydrocarbons, nitrogen-oxygen compounds,sulphur compounds and spilled crude oil or refined petroleum fractions like lubricant oils or gasoline may lead to harsh and long-term effects on plants and wildlife.Figure 2 shows the ecotoxicological influence of oil pollution on the environment. The complexity and toxicity of hydrocarbons present in crude oil makes the cleanup to be complicated. Thermal,chemical, biological and physical processes are known methods that can be employed in controlling the contaminated site. These techniques can be singly applied or in combination with other cleaning techniques based on the pollutant's amount, type and the environment. Each of the approaches has its own disadvantages and advantages.Both physical and chemical methods are usually recognized as principal methods which are adopted for practical remediation and to curb oil accumulation [11].

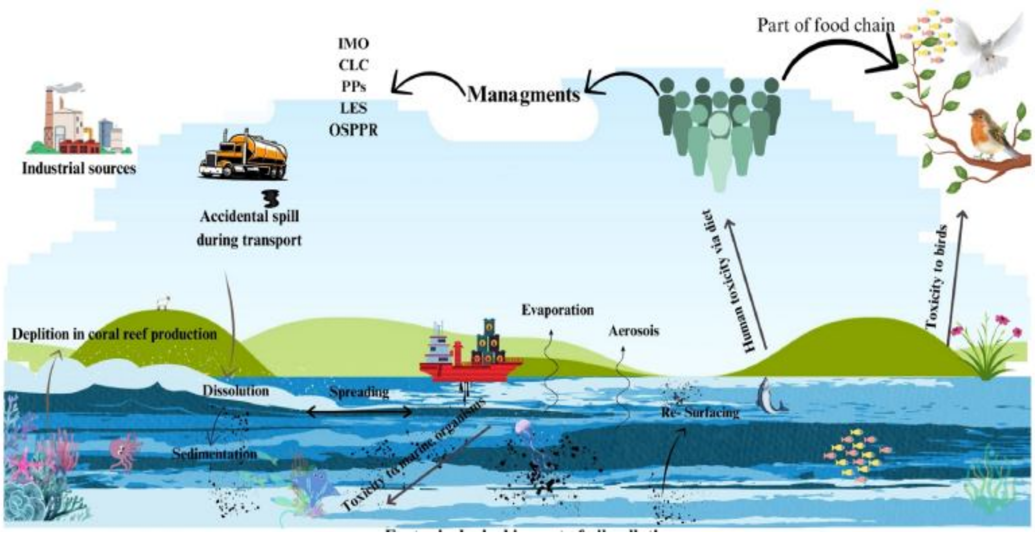

Figure 2: Ecotoxicological influence of oil pollution on the environment

Oil removal from water can be achieved via applying different oil remediation techniques. Physical, chemical, biological and thermal remediation methods are the four principal classificationsinto which present treatments can be categorized. Physical techniques of cleaning up include booms, sorbent materials and skimmers. It stops oil booms and spills from expanding.In chemical remediation methods, solidifiers and dispersants are applied in cleaning up of oil spills. Microbes are applied in biological remediation methods to catalyzeoil constituents' natural breakdown. Waves are applied to trap oil spills, and thermal cleanup techniques include simply booms lighting [12]. The best technique will depend on many factors which indirectly or directlyimpact the repair methods. A few of these factors include the oil spillvolume, oil spillcharacteristics, tidal wave patterns and ambient temperatureat the spill site and the hazard the oil spill poses to the human population,the surrounding environment, and significant commercial and cultural locations.

This pollution resulting fromoil leak requires to be cleaned up instantly. One way to achieve this is via phytoremediation which is a vitalelement of biological remediation that centers only on applying plants to contain, absorbor eliminate pollutants from their surroundings viatransformation or absorption. Numerous plant species have shown high efficacy of treating polluted soils and eliminating pollutants from the growth media. These plants may achieve this on their own or in collaboration with microbes.A rich toolset is being built currently by practitioners and researchers in combating pollution, including bioremediation,phytoremediation, complex analytical methods and monitoring systems [13]. This review article explores the recent noveldevelopments in environmental cleanup,evolving challenges and innovative methods aiming at minimizingpollution impact. The recent remediation techniques and technology for the emerging pollutants in order to enhance public health and ecosystem resilience in our environment are discussed.

2.0 EMERGING ENVIRONMENTAL POLLUTANTSAND THEIR CLASSIFICATIONS

The variety of toxins group with the potential of endangering human health and ecosystems are called emerging environmental pollutants. Personal care products and pharmaceuticals such as hormones,sunscreens, antibiotics and perfumes are emerging pollutants. Industrial and domestic wastewater releases, agricultural runoff and inadequate prescription disposal discharge these toxins into the environment. Personal care products and pharmaceuticalsare bio-accumulative in nature and may injure aquatic endocrine systems.Microplastics are another set of major emerging contaminant which are lesser than 5 mm.They originate from more substantial plastic waste division,microbeads in personal care items and synthetic fibers lost after washing from fabrics [4]. These particles can remain in the environment and find their ways into the food chain, threatening marine life. Synthetic compounds referred to as per- and polyfluoroalkyl are utilized in consumer and industrial items to repelgrease and water.

Personal care products and pharmaceuticalsare tenacious and found in soil, water and animals worldwide. Their pollution emanates from waterproof fabrics, firefighting foams, industrial emissions and non-stick cookware. Endocrine-disrupting chemicals interrupt animal and human hormonal systems and are recognized as another emerging group of contaminants.Figure 3 shows the effects of heavy metals, antibiotics and pharmaceuticals on human health. The major identified effects include abnormal bone; damaged organs and growth deformities; abnormal foetus; testicular and uterine damage; abnormal pregnancy and so on. Endocrine-disrupting chemicals in flame retardants, insecticides and plastics can enter the environment via agricultural runoff, industrial discharges and atmospheric deposition [7]. Endocrine-disrupting chemicals can causedevelopmental and reproductive problems in wildlife and aquatic lives.Industrial chemicals such as surfactants, plasticizers and flame retardants applied in consumer and manufacturing goods, are developing contaminants. Also, these chemicals may be released by landfills,industrial sites and urban runoff, threateninghumans and ecosystem. Emerging contaminants originate from manyinterconnected sources, revealing the difficulty of contemporary consumer andindustrial habits. Emerging contaminants must be tackled at the origin, treatment techniques of wastewater should be improved, and novel remediation techniques should be developed to handle their issues. The knowledge of emerging contaminants' types and sources can assist stakeholders in developing better pollution mitigation measures for the public health and environment [12].

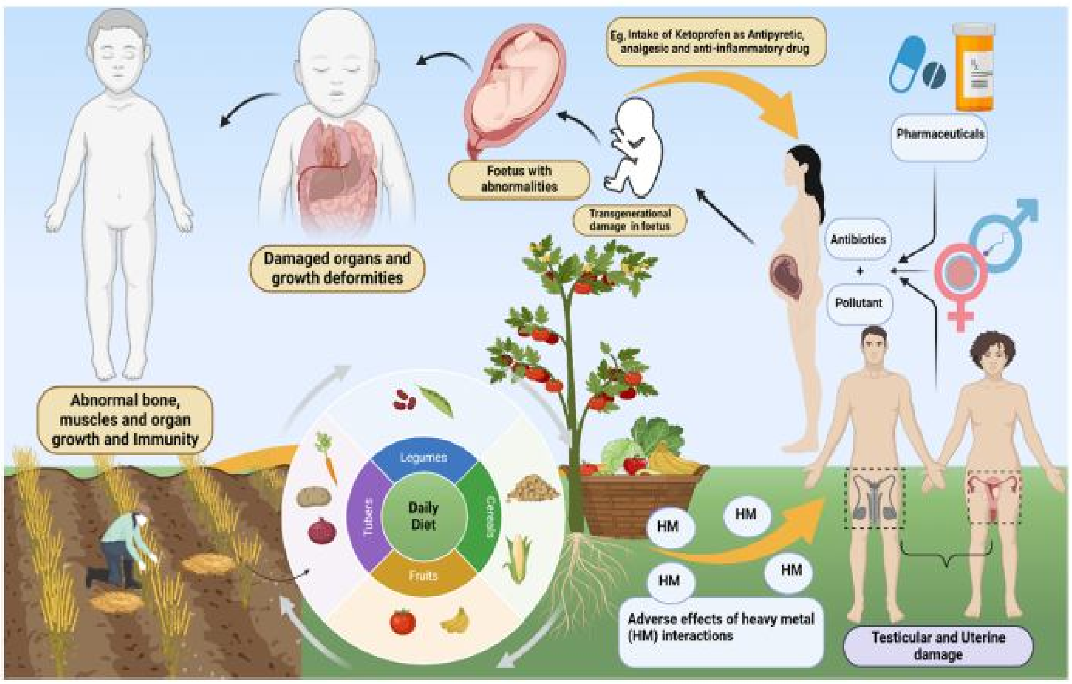

Figure 3: Schematic diagram showing the effects of heavy metals, antibiotics and pharmaceuticals on human health

Emerging pollutants are toxins which are recognized for their environmental availability and accorded health risks. Novel attributesand chemical structures of these contaminants make pollution handling and its cleanup tasking. Agricultural activities,industrial operations, urban runoff, medicines and personal care productsmay generate emerging contaminants. They may find their way into the environment viawastewater discharges, air deposition and inappropriate disposal [14]. Emerging pollutants include personal care products and pharmaceuticals which include numerous chemicals in cosmetics, drugs and hygiene items. These chemicals may remain persistence in the environment and hurtecosystems and aquatic creatures. Elements that disruptpharmaceutical residues and hormonal systems may pollute water supplies and aquatic environments, which are other developing contaminants. Emerging contaminants are categorized viaenvironmental destiny and attributes, chemical constituents, sources and possible consequences. In order to effectively reduce the release of these emerging contaminants, preserve human health, conserve ecological integrity and monitor their environmental availability, the knowledge of their classification and description are imperative [15]. Also, continual investigation and collaboration by policymakers,scientistsand stakeholders is essential on these novel toxins for sustainable environmental management and efficient pollution mitigation.

2.1 SOURCES AND PATHWAYS OF CONTAMINATION

Contaminationroutes and sourcesinclude several natural and human processesthat spread and introduce contaminants. Industrial emissions from power plants, industrial facilities and factoriespollute the land, water and air.Volatile organic compounds, heavy metals and toxic chemicals may contaminate the ecosystems and hurt humans via ingestion, inhalation and cutaneous contact. Waterways are polluted by agriculture via the release of toxins and nutrients from herbicides,pesticides and fertilizers [7].Algal blooms,eutrophication,nitrogen, phosphorus and pesticide residue contamination of groundwater and surface water may be caused by agricultural runoff.Land and water may also be polluted with hormones, antibiotics and diseases vialivestock activities. Stormwater runoff,sewage discharge and solid waste disposal may also pollute municipalities. Personal care products,pharmaceuticalsand other related chemicals may find their path into lakes,rivers and seasfrom wastewater treatment facilities that was unable to eliminate pollutants. Solid waste poor disposal including electrical, plastic and toxic materials may pollute aquatic and land areas, threateningecosystems and species. The environment is polluted by contaminants which are generated naturally such as volcanoes, weathering and erosion [9].

The release of ash, sulfur dioxide and other particulate gases via volcanic eruptions may alter the air quality and cause acid rain. Heavy metals and other toxins can be discharged into waterways through sedimentary rocks erosion and polluted soilsweathering. Environmental circumstances, type of pollutants and human activity hinder the way toxins spread in the environment.Common contamination mechanisms are leaching and airborne deposition. Pollutants can be transferred from surface runoff into the surrounding waterways. The concentrations of the pollutants in food chain creatures can be raised by biomagnification and bioaccumulation [4]. Knowledge regarding contamination pathways and origins is required to effectively manage pollution and protect the environment and public health. Pollution techniques must include the intricate correlations between natural processes, human activities, and environmental systems. This enhances the control of pollution, reduction of pollutant emissions and promotion of sustainable environmental stewardship. There is need for novel environmental remediation techniques [5].

3.0 NOVEL ENVIRONMENTAL REMEDIATION TECHNIQUES

The adoption of nature's methods as bio-inspired solutions to tackle complex environmental problems has gained popularity in environmental science and engineering field. These solutions involve using biological systems, structures and processes in minimizing pollution, enhance ecological health and restore ecosystems.Novel environmental remediation techniques for pollutants removal to enhance public health and ecosystem resilience are bioremediation, advanced oxidation processes, nanotechnology and using biomimetic materials and coatings.

- **Bioremediation**

Bioremediation entails using biological organisms in the removalor neutralization of an environmental pollutant via metabolic route. The utilized biological organisms are microscopic organisms such as bacteria, algae and fungi. Microorganisms' growth is within the broad range of habitatsin the Earth's biosphere. They can grow in plants, deep sea, water, soil, animals and freezing ice environment [16]. The potential of microorganisms which make them to be perfect environmental cleanser lies in their absorbing appetite for different kinds of chemicals and their outright numbers. Bioremediation is a technique of managing our wasteswhich requires using living organisms to eliminate or deactivate contaminants from a polluted site. Bioremediation is a treatment method that utilizes naturally existing organisms to destroy toxic substances into less harmful or non-harmful materials.

The evolution of bioremediation technologies has been very contributory in environmental science and engineering field and it's growing as at today is at exponential rate. Remediation of contaminated sites applying microbial process (bioremediation)has exhibited reliable and effective results due to its eco-friendliness attributes. The decisive objective of using bioremediation methods is to perfectly revive contaminated environments in an eco-friendly and economic technique. The advancements in bioremediation methods in the last two decades have been so tremendous. Various bioremediation approaches have been developed by current researchers in order to restore the contaminated environments. The micro-organisms applied in bioremediationcan either be non-indigenous or indigenous added to the polluted site.Home-grown microorganisms available in contaminated environments are crucial in solvingmany of the challenges linked with bioremediation and biodegradation of pollutant.Cost effectiveness and environmentalfriendliness are among the principal benefits ofbioremediation when compared with physical and chemical techniques of remediation [17].

Bioremediationmechanism involves detoxification, mineralization, reduction, transformation or degradation of more toxic contaminants toless toxic ones. The nature of the pollutant is a major influencing factor for the removal process of the pollutants. The pollutants include chlorinated compounds,organic halogens,pesticides,heavy metals,dyes plastics, greenhouse gases,agrochemicals,nuclear waste,xenobiotic compounds, hydrocarbons and sludge.Cleaningprocedure is applied in removing the hazardous wastes from contaminated environment. Bioremediationis exceedingly involved in detoxification, eradication, degradation and immobilization of different physical toxic materials and chemical wastes from the surroundingviamicroorganisms action [18]. Figure 4 represents the classification tree of bioremediation which is sub-divided into in-situ and ex-situ bioremediation. The in-situ bioremediation is classified into intrinsic and engineered bioremediation. Various kinds of novel engineered bioremediation include biosparging, bioventing, bioslurping, biostimulation, bioaugmentation and natural attenuation. The ex-situ bioremediation is sub-divided into slurry phase and solid phase bioremediation. The slurry phase bioremediation simply involves the use of bioreactor. Biopiling, land farming, composting and biofilter are the sub-categories under the solid phase bioremediation [12].

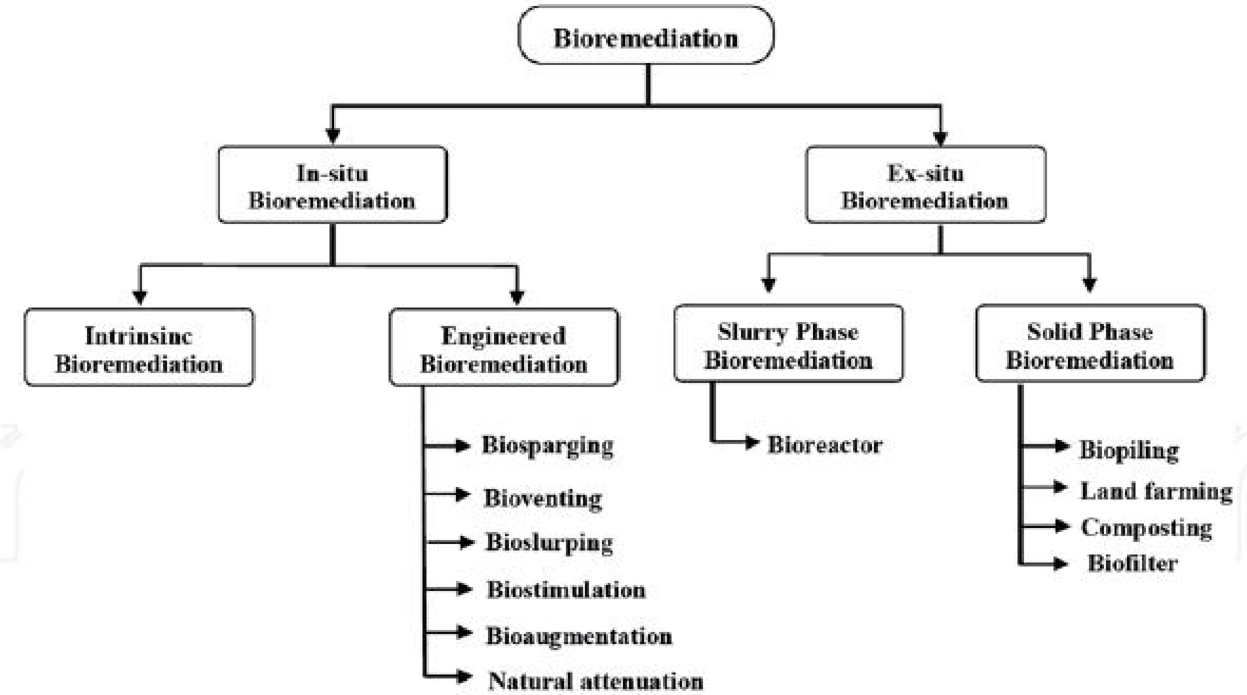

Figure 4: Bioremediation techniques for treatment of contaminated environment

- **Advanced Oxidation Processes**

One of the foremost methods of cleaning environment with pollutants is Advanced Oxidation Processes (AOPs). This is mostly applicable in removing contaminants in water. Extremely reactive species (such as hydroxyl radicals) are generated by these processes to degrade the most adamant pollutants.Current innovations in this regard involve using modified catalysts, such as Fe-based and TiO_2materials, which have the potential to increase photocatalytic processes efficiency under the control of visible light [19]. However, the consumption of energy utilization under APOs, despite their unique effectiveness, is quite challenging together with the synthesis of by-products which are toxic in nature. Future studies should critically look into this to lower the required energy and also improve its selectivity to broaden the acceptance and application of this technology.

- **In situ chemical oxidation and Nanotechnology**

Another innovative method being applied in the direct treatment of contaminated sites is the in situ chemical oxidation (ISCO). During the process, oxidizing agents are injected into the ground to distingerate the pollutants present. The development ofeffective and more stable oxidants which have the capacity to break down wider contaminants range are also other recent advancements. ISCO is mainly applied in remediating groundwater andsoil but needs cautious control to prevent adverse effects on the surrounding environments [20].Nanotechnology is another novel powerful instrument used in emerging pollutantsremediation, enhancing public health and ecosystem resilience. Nanomaterials such as metal-organic frameworks (MOFs) and graphene oxide can be utilized in adsorbing and degrading pollutants at the molecular level. These materials are characterized with high reactivity and surface area which supports their efficiency in the removal of contaminants from soil and water. The regeneration, recovery and thermal stability of these materials are needed to be investigated further by future studies [21].

- **Biomimetic materials and coatings**

Another novel and recent bio-inspired environmental remediation alternative involves using biomimetic materials and coatings. Shark skins and lotus leaves have motivated researchers in establishing anti-fouling, self-cleaning and anti-bacterial surfaces. Biomimetic materials are employed in water treatment techniques to eliminate chemical additives, preventmembrane biofouling and improve filtering activity. Bio-inspired environmental pollution monitors and sensors are another bio-inspired method [22-23].Fish and bee sensory systems have been imitated by scientists in the construction of selective and sensitive sensors to recognize volatile chemical compounds, heavy metals and microbial infections. Early detection of pollution can be attained through bio-inspired sensors for real-time monitoring. This gives cogent information in making tangible and applicable environmental management decisions. Bio-inspired autonomous and robotssystems also enhance environmental cleanup and monitoring.

4. CONCLUSION

In conclusion, in order to degrade contaminants, revive ecosystem health and protect human health, environmental remediation is vital. This review article critically examines novel remediation techniques for new contaminants and prospective innovative and technological advances in cleaning environment for ecosystem resilience and enhancement of public health. Recognized emerging contaminants threatening public health and environmental quality include microplastics,heavy metals, pharmaceuticals and industrial chemicals. Novel research, proactive monitoring and regulation are imperative to reduce the concentrations of these toxins present in air, soil and water. To tackle these problems, novel remediationtechnologies and procedureshave been established and used for particular pollutants. Novel environmental remediation techniques for pollutants removal to enhance public health and ecosystem resilience are bioremediation, advanced oxidation processes, nanotechnology and using biomimetic materials and coatings. In conclusion, it is imperative to give superiority to rehabilitation and remediation initiatives in order to ensure there is ecological justice. Pollution can be overcome;ecological quality can be restored; and more resilient and healthier environment can be built via innovative and collaborative research in environmental science and engineering field.

REFERENCES

1. Ajala, O.J., Tijani, J.O., Salau, R.B., Abdulkareem, A.S., Aremu, O.S. A review of emerging micro-pollutants in hospital wastewater: environmental fate and remediation options. Result. Eng., 2022, 16, 100671.

2. Bejarano, J.B.P., Sossa, J.W.Z., Ocampo-L´opez, C., Ramírez-Carmona, M. Open innovation: a technology transfer alternative from universities. A systematic literature review. J. OpenInnov. Technol. Mark. Complex., 2023, 9, 100090.

3. Jiang, D., Fang, D., Zhou, Y., Wang, Z., Yang, Z., Zhu, J., Liu, Z. Strategies for improving the catalytic activity of metal-organic frameworks and derivatives in SR- AOPs: Facing emerging environmental pollutants. Environ. Pollut., 2022, 306, 119386.

4. Junaid, M., Siddiqui, J.A., Liu, S., Lan, R., Abbas, Z., Chen, G., Wang, J. Adverse multigeneration combined impacts of micro(nano)plastics and emerging pollutants in the aquatic environment. Sci. Total Environ., 2024, 882, 163679.

5. Kroon, N., Alves, M.do C., Martins, I..The Impacts of emerging technologies on accountants' role and skills: connecting to open innovation—a systematic literature review. J. OpenInnov. Technol. Mark. Complex., 2024, 7, 163.

6. Li, S., Ondon, B.S., Ho, S.-H., Li, F.. Emerging soil contamination of antibiotics resistance bacteria (ARB) carrying genes (ARGs): new challenges for soil remediation and conservation. Environ. Res., 2023, 219, 115132.

7. Kumar, A., Nighojkar, A., Varma, P., Prakash, N.J., Kandasubramanian, B., Zimmermann, K., Dixit, F. Algal mediated intervention for the retrieval of emerging pollutants from aqueous media. J. Hazard. Mater. 2023, 455, 131568.

8. Malerba, M.E., Duarte de Paula Costa, M., Friess, D.A., Schuster, L., Young, M.A., Lagomasino, D., Serrano, O., Hickey, S.M., York, P.H., Rasheed, M., Lefcheck, J.S., Radford, B., Atwood, T.B., Ierodiaconou, D., Macreadie, P. Remote sensing for cost-effective blue carbon accounting. Earth-Science Rev, 2023, 238, 104337.

9. Mishra, R.K., Mentha, S.S., Misra, Y., Dwivedi, N.. Emerging pollutants of severe environmental concern in water and wastewater: a comprehensive review on current developments and future research. Water-Energy Nexus, 2023, 6, 74–95.

10. Taoufik, N., Sadiq, M., Abdennouri, M., Qourzal, S., Khataee, A., Sillanp, M., Barka, N. Recent advances in the synthesis and environmental catalytic applications of layered double hydroxides-based materials for degradation of emerging pollutants through advanced oxidation processes. Mater. Res. Bull., 2024, 154, 111924.

11. Mishra, R.K., Mentha, S.S., Misra, Y., Dwivedi, N.. Emerging pollutants of severe environmental concern in water and wastewater: a comprehensive review on current developments and future research. Water-Energy Nexus, 2023, 6, 74–95.

12. Gangani, N., Joshi, V.C., Sharma, S., Bhattacharya, A. Fluoride contamination in water: remediation strategies through membranes. Groundw. Sustain. Dev., 2022, 17, 100751.

13. Thirumurugan, D., Kokila, D., Balaji, T., Rajamohan, R., AlSalhi, M.S., Devanesan, S., Rajasekar, A., Parthipan, P. Impact of biosurfactant produced by Bacillus spp. on biodegradation efficiency of crude oil and anthracene. Chemosphere, 2023, 344, 140340.

14. Sun, J., Khattak, W.A., Abbas, A., Nawaz, M., Hameed, R., Javed, Q., Bo, Y., Khan, K.A., Du, D. Ecological adaptability of invasive weeds under environmental pollutants: A review. Environ. Exp. Bot., 2023, 215, 105492.

15. Waqas, M., Wong, M.S., Stocchino, A., Abbas, S., Hafeez, S., Zhu, R., 2023. Marine plastic pollution detection and identification by using remote sensing-meta analysis. Mar. Pollut. Bull., 2023, 197, 115746.

16. Samriti, Rumyantseva, M., Sun, S., Kuznetsov, A., Prakash, J. Emerging nanomaterials in the detection and degradation of air pollutants. Curr. Opin. Environ. Sci. Heal., 2023, 35, 100497.

17. Nishad, P.A., Bhaskarapillai, A.,. Antimony, a pollutant of emerging concern: a review on industrial sources and remediation technologies. Chemosphere, 2021, 277, 130252.

18. Zhou, Xian, Wang, T., Wang, J., Chen, S., Ling, W. Research progress and prospect of glomalin-related soil protein in the remediation of slightly contaminated soil. Chemosphere, 2024, 344, 140394.

19. Solangi, N.H., Karri, R.R., Mazari, S.A., Mubarak, N.M., Jatoi, A.S.,Malafaia, G., Azad, A. K..MXene as emerging material for photocatalytic degradation of environmental pollutants. Coord. Chem. Rev., 2024, 477, 214965.

20. Janga, J.K., Reddy, K.R., Raviteja, K.V.N.S.. Integrating artificial intelligence, machine learning, and deep learning approaches into remediation of contaminated sites: a review. Chemosphere, 2024, 345, 140476.

22. Quarshie, P., Asefon, T.S. Data-driven techniques and data analytics in water treatment facilities: Innovative safety protocols and optimization. J. Geography, Environment and Earth Science International, 2024, 28, 10, 65-77.

23. Behera, S., Das, S. Potential and prospects of Actinobacteria in the bioremediation of environmental pollutants: cellular mechanisms and genetic regulations. Microbiol. Res., 2023, 273, 127399.