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REVOLUTIONISING HEAVY METAL DEGRADATION: NOVEL METHODS AND TECHNOLOGICAL ADVANCES

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ABSTRACT

Heavy metal contamination in water sources severely threatens the environment and public health. The remediation methods followed so far lack satisfactory efficiency, selectivity, and sustainability. This paper presents novel methods and technological developments for heavy metal degradation, including nanomaterial-based remediation, advanced oxidation processes, and hybrid coagulation techniques. The most recent developments in nanotechnology have proved to have a potential for the improvement of selectivity and efficiency in the removal of heavy metals; graphene oxide, carbon nanotubes, and metal-organic frameworks are some of the best adsorbents

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with good capacities. Chemical desorption, electrochemical regeneration, and photocatalytic regeneration have also been developed in such a way that reusability and cost-effectiveness have improved greatly. The current release discusses these two novel technologies together with respect to their scalability's and their ecological impacts that occur due to its application while stressing the imperative involvement of multi responsivity alongside the proper inductees as well under green chemistry and possible future areas regarding research challenges that may unfold their way.

Keywords: heavy metal, environment, desorption, nanotechnology, green chemistry, hazardous chemicals.

AIMS AND BACKGROUND

Heavy metal contamination is currently an environmental issue of hitherto previously unimagined size and, to human health and the ecosystem, at very grave risk. The metals concerned are lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) and are not degradable but remain in the environment for much too long a duration and in soil, water, and even in living tissues. Heavy metal pollution impacts vary from the extensive range of industrial effluent, mining, and agricultural run-off to secret dumping of refuse. The toxic activity of the heavy metals is variegated in character, causing bio amplification in the food chain, biological malfunctioning, and poisonous health conditions such as neurological disease, organ dysfunction, and even carcinomas[1]. Traditional heavy metal remediation technologies like chemical precipitation, ion exchange, and membrane filtration have been extensively applied[2]. Plants are being used different treatments in folk medicine. Evaluation of the antibacterial, *in vitro* anti-diabetic, and larvicidal properties of *Mentha arvensis* L., *Allium sativum*, and *Zingiber officinale* plants was the study's main goal[3]. The *Illicium verum* (star anise) has an extended tradition of usage in traditional medicine and the food industry for its anti-cold and pain-relieving properties. Evidence of *Illicium verum*'s traditional applications comes from south and west Asia, where it has been used to treat a variety of ailments[4]. The use of herbal medicines and phytonutrients is quickly spreading around the world due to their effectiveness and lack of adverse effects[5]. The use of herbal medicines and phytonutrients is quickly spreading around the world due to their effectiveness and lack of adverse effects[6].

Continuing with plant's applications in healthcare, new technologies have facilitated new ways for the degradation of heavy metals. These are the use of new technologies and interdisciplinarity to the task of cost-effectiveness, effectiveness, and eco-friendliness of remediation. Of these, bioremediation is especially noteworthy since it is at the centre in the use of microorganisms, plants, and enzymes in heavy metal decontamination. Among the likely mechanisms are biosorption by microorganisms, phytoremediation, and enzymatic breakdown of the intrinsic bias of the biological system toward the removal of heavy metals from the contaminated system[7]. The removal of heavy metals has also changed with the onset of nanotechnology.

The discovery of novel nanomaterials, such as graphene oxide, carbon nanotubes, and metal-organic frameworks, has introduced novel paradigms toward heavy metal removal as efficient and selective agents. The nanomaterials have unique properties, i.e. high surface area, surface tunability, and suitable adsorption capacity, which make them most appropriate to be used as future technology for remediation. Moreover, a combination of nanotechnology with other technologies, i.e. photocatalysis and electrochemistry, has even made the removal of heavy metals more efficient[8]. Another highly promising field of research is the application of green chemistry principles towards designing green and sustainable remediation technology. Moreover, studies on hybrid processes with integration of more than one method, e.g. nanotechnology and bioremediation, have also been found to possess great potential to fill the gap of a technology limitation. Despite all this success, a few heavy metal degradation problems remained, which could not be tackled. Economic feasibility and scalability of new interventions on the economic front, hazard of nanomaterials, and conditions for effective regulation policy are among the most important issues that need to be addressed. Real-time monitoring and assessment schemes must also be designed in such a way that it would be feasible to determine if the remediation activity is effective or not and how it would provide assurance in terms of their sustainability for a longer duration[9].

EXPERIMENTAL

In characterisation of nanoparticles Scanning Electron Microscopy (SEM) characterised the particle size and morphology. The characterisation of the crystalline phase was facilitated with the assistance of X-Ray Diffraction (XRD) along with phase purity determination. Surface functionality and chemical groups were examined with the assistance of Fourier-Transform Infrared Spectroscopy (FTIR) (Ref. 10). Batch Adsorption Experiments: Added known concentration heavy metal synthetic solutions (e.g. Pb^{2+}, Cr^{6+}). Suspended the nanoparticles in the solutions and shaken the solutions in a rotary shaker. Residual metal ion concentrations were measured using Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Ref. 11).

BIOREMEDIATION PROCEDURES

Procedures used biological agents such as microorganisms and plants to eliminate heavy metals from the pollutes: in microorganism culture, the heavy metal resistant bacterial isolates *Pseudomonas aeruginosa* and *Bacillus subtilis* were obtained from spiked heavy metal soil samples. Bacteria were seeded in nutrient broth and incubated at 37°C for 24–48 h for improved growth. For heavy metal biosorption studies, the bacterial cultures were treated with the heavy metal solutions in the best possible condition, i.e. pH, temperature, and aeration. The efficiency was verified by measurement of metal concentration before and after treatment by AAS or ICP-MS.

In phytoremediation design, *Brassica juncea* hyperaccumulator plants were grown in hydroponic apparatus utilising heavy metal-contaminated water. EDTA-like chelating compounds were employed for greater metal accumulation. Acid digestion and AAS were utilised for the determination of tissue accumulated metal concentration levels[12].

Electrochemical techniques were applied for the degradation of heavy metals, i.e. setup of electrocoagulation reactor: Aluminium anode with cathode was used. Target electrolyte solution of heavy metal ions was used. DC power supply was used, and the voltage and current density were regulated for optimum efficiency. In electro flotation process microbubbles generated by electrolysis were supplied with metal particle-aggregated solutions. Flow rate and bubble size were regulated for optimum separation of metal impurities. In electrochemical characterisation, the electrode performance was studied using cyclic voltammetry and the mechanism of reaction. Removal efficiency was measured quantitatively from assured treated solutions employing ICP-MS (Ref. 13). Reactive oxidative species utilised in oxidation of heavy metals by following processes like photocatalytic degradation where TiO_2 nanospheres were dispersed in a reactor with heavy metal solutions charged in it. The reactor was irradiated by UV light, and time-based reaction kinetics was monitored. Reduction in metal toxicity was monitored using spectrophotometry.

In Fenton and photo-Fenton reactions, aqueous Fe^{2+} salts were combined with H_2O_2 in the acidic medium to produce hydroxyl radicals. Complete degradation was achieved using UV irradiation in the photo-Fenton process. Reducing metal ion was determined by AAS or spectroscopic techniques. Analytical and optimisation protocols carried out experimental results significantly[14]. For sample preparation acid-digested or filtered samples were conducted prior to analysis to prevent interference. Normal handling of the sample was carried out to prevent loss of reproducibility. Hardware of interest, i.e. AAS and ICP-MS, was utilised to measure the residual metal ions and determine removal efficiency[15].

TRADITIONAL METHODS OF HEAVY METAL DEGRADATION

Traditional heavy metal degradation processes have worked significantly to save the environment from pollution in methods such as chemical precipitation, ion exchange, membrane filtration, adsorption, electrochemical treatment, and phytoremediation. The process of precipitation of metal ions as insoluble compounds that may be removed as precipitates has been used in chemical precipitation, as shown in Fig. 1, although much sludge is created, which requires secondary treatment. Ion exchange is a cost-effective, selective process reliant on synthetic resins to exchange deadly metal ions with non-toxic ones. Still, it is marred with the fouling of the resin and cost[16]. Membrane separation technologies, including nanofiltration and reverse osmosis, are highly effective in removing heavy metals even at trace levels but are energy-intensive, need constant maintenance, and are prone to fouling. Adsorption, which is simple and inexpensive, employs substances such as clay minerals and activated carbon to trap metal ions from contaminated environments, but its effectiveness is dependent on contaminant concentration and type[17]. Electrochemical processes, for instance, electrocoagulation and electrodialysis, employ electricity to enable aggregation and recovery of heavy metals and therefore offer green alternatives though limited by high energy consumption and sophisticated equipment to be applied universally. Phytoremediation exploits the inherent ability of some plants to uptake and deposit heavy metals in polluted water or soil at low expenses and minimal environmental effects, albeit slowly and with restrictions by plant tolerance and accumulation capacity[18].

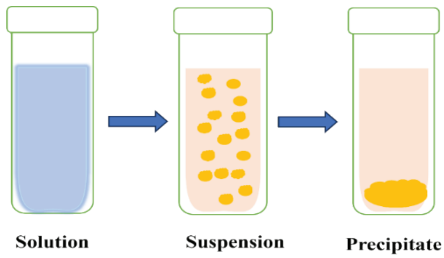


Fig. 1. Traditional method (chemical precipitation)

EMERGING NANOMATERIAL-BASED APPROACHES

Current nanomaterial-based technologies have transformed the degrading process of heavy metals through innovative solutions far beyond the confines of conventional technology[19]. The best nanomaterial for heavy metal removal is metal and metal oxide nanoparticles. They are among the most efficient nanomaterials such as zero-valent iron (ZVI), titanium dioxide (TiO_2), and zinc oxide (ZnO) that have been most efficient in heavy metal adsorption and degradation. ZVI nanoparticles, for instance, have been used extensively in remediation of highly toxic heavy metals such as chromium (Cr(VI)) to their less toxic form by redox processes shown in Fig. 2 (Ref. 20).

Carbon nanomaterials including graphene oxide (GO), carbon nanotubes (cnts), and activated carbon nanofibers are also being used of special interest in the process of heavy metal removal. They possess very high surface area and functionalise surface and possess good absorptivity as well. For example, GO is chemically modified with some sort of chemicals like carboxyl or amino as an effort to render it selective in heavy metal ions adsorption process[21]. Metal–organic frameworks (MOFs) are crystalline, porous solids formed by the coordination between metal ions and organic ligands. This unique structure imparts high porosity and an exceptionally large surface area to the material. Metal–organic frameworks possess tunable pore size and surface functional groups for selective heavy metal adsorption and removal. For example, MOFs were successfully utilised to adsorb mercury (Hg), cadmium (Cd), and lead (Pb) ions from water and proved themselves to be efficient and handy. The applications of nanotechnology to other remediation processes apart from adsorption also enhanced the extent of efficiency for the decontamination of heavy metal. For example, nano-bio hybrid systems prepared on the basis of nanomaterial synergism of bioremediation. They achieved very high remediation efficiency through the synergism between biotic factors like enzymes or microbes and nanomaterials[22].

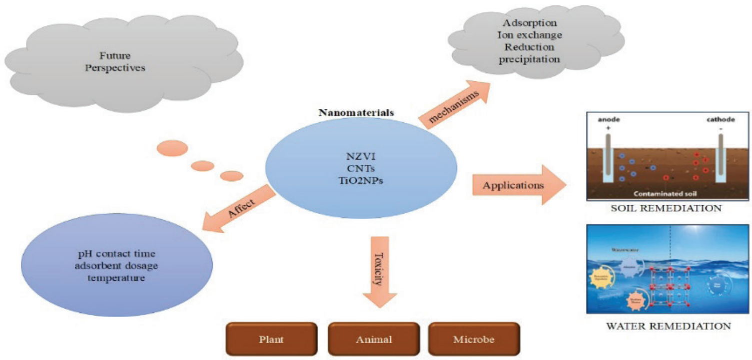


Fig. 2. Nanomaterials-based heavy metal degradation

RESULTS AND DISCUSSION

TECHNOLOGICAL ADVANCES IN HEAVY METAL DEGRADATION

Heavy metal degrading technology is currently enhanced by virtue of the presence of new technology that is innovative, environmentally friendly, and efficient in having effective remediation processes. New technologies based on underdisciplined combine biology, chemistry, physics, and engineering into effective heavy metal remediation that enhances the process compared to the earlier traditional ones with an added feature for heavy metal remediation. For reversing some of the newest technology of the degradability of heavy metals, humongous followings are controversial elaborate elaborated fully below in detail (Table 1). The advancements hitherto have been deepest in technology development in the field of applying nanotechnology to fabricate nanoscale materials with engineered characteristics for the removal of heavy metals[23]. Zero-valent iron (ZVI), titanium dioxide (TiO_2), and graphene oxide (GO) nanoparticle are also employed with higher surface area, high activity, and better degradation and adsorption property for the metal ions. The compounds can target the target metals such as mercury (Hg), lead (Pb), and cadmium (Cd) specifically and effectively. Heavy metal pollutants can now be decomposed with high efficiency by photocatalysis, which has been integrated with advanced nanotechnology under sunlight or ultraviolet exposure, promoting a new benchmark in environmental sustainability and energy-neutral remediation[24]. Genetic engineering and bioremediation are being utilised with the presumption to increase the capacity of plant and microbe towards detoxification of heavy metal to a natural degree. Microorganisms like fungi and bacteria are becoming more resistant and degradation potential and synthetic biology approaches are yielding selective design promise of tailor-made biosystems for the sequestration of heavy metals and their conversion effectively. Transgenic plants associated with phytoremediation are designed to increase their uptake, translocations, and detoxification of a single metal and hence improve scalability and efficiency in the green technology. Electrochemical approaches come unbilled with innovative options for the selective removal and removal of heavy metals. Electrocoagulation, for instance, utilises electric current to disperse and coagulate freely dispersible metal particles into flocs. Electrodialysis is a process of concentration and transport of metal ions from contaminated solutions through the assistance of ion-exchange membranes and an electric field and hence is a very effective treatment process for treatment of complex waste streams. Additionally, electrochemical reduction can be utilised to convert toxic heavy metal ions to less toxic forms, and such a treatment is a versatile and flexible treatment[25]. One of the characteristics of growth on a rapid scale is application of adsorptive and catalytic materials to purify heavy metals. Heavy metals in pollutants have been distinguished by materials such as metal-organic frameworks (MOFs), functionalised biochar (FCBs), and hybrid composites because of improved selectivity and reusability. Metal Organic Frameworks, based on the functional group and compositional modularity, show effective adsorption and immobilisation of heavy metals from solution. Zeolites and cerium oxide nanoparticles are utilised for use in metal complex degradation and in degradation efficiency. Processes using membranes such as nanofiltration, reverse osmosis, and ultrafiltration have also made great developments over recent years. Membrane processes were observed to be of very high selectivity and efficiency in heavy metal separation. Nanostructured materials that played a major role in the improvement of new design of membranes resulted in improved fouling resistance and lifetimes. Hybrid technologies, which are combinations of combinations of filtration with others like adsorption or bioremediation, are more efficient and versatile in operation[26]. It is also a groundbreaking new generation of heavy metal decontamination. AI models forecast contaminant trends, remediation treatment protocols, and treatment efficiency processes. Machine learning algorithms can identify concealed trends in ginormous data sets and recommend transparent solutions to particular environmental conditions by inspecting ginormous data sets at reduced operational costs and validating remediation choices. Finally, clean and green technology is also leading to the development of environmentally friendly processes for heavy metal degradation. Green chemistry approaches such as plant biomass-derived biosorbents, biochar, and biocompatible nanomaterials are being utilised in order to minimise the green footprint of the treatment process. Solar- or microbe-operated fuel cells are also being utilised in the remediation process to achieve maximum energy extraction and sustainability. Briefly, technologies have driven the power and size of heavy metal degradation technologies far ahead. Through biotechnology and nanotechnology, electrochemistry and AI technology, inventions are solving next-generation challenges and charting the course to a cleaner and healthier world. In addition to advancements in science, research priorities in cross-discipline, sustainability, and application-oriented research will be important in realising the potential of these paradigm-based technologies[27].

Table 1. Technological advances in heavy metal degradation

Technology	Description	Example Materials/Methods	Benefits
Nanotechnology	Use of engineered nanomaterials for metal removal and degradation	ZVI, TiO_2, GO	High surface area, effective targeting of specific heavy metals
Biotechnology	Genetic engineering and microbial utilisation for natural detoxification	Microbes, transgenic plants	Enhanced uptake, scalability, environmentally friendly
Electrochemical methods	Electric current-based separation and reduction of heavy metal toxicity	Electrocoagulation, electrodialysis	Selective removal, versatility for complex waste streams
Adsorptive materials	Materials engineered for better adsorption and reuse	MOFs, functionalised biochar	High selectivity, reusability
Membrane technologies	Filtration methods with advanced designs for metal separation	Nanofiltration, reverse osmosis, ultrafiltration	High efficiency, fouling resistance, long lifespan

CHALLENGES AND LIMITATIONS

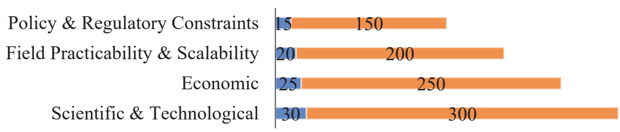
The field of heavy metal degradation, though reflecting vibrant advancement in the past three decades, is also riddled with several challenges and limitations to be overcome for remediation technology to become successful, scalable, and sustainable. They are as under: scientific and technological, economic and social, from research and innovation to multi-disciplinary interventions. The majority among them is heterogeneity and complexity of contaminated media[28]. Pollution with heavy metals in various environments including industrial wastewaters and farm drainage, mines, and city soils is very common. Each of these above-listed environments has common aspects like pH, temperature, salinity, and co-pollutants which influence remedial processes efficacy. For instance, conventional adsorptive systems suffer from inferior efficacy with disturbing ions or organic compounds. This heterogeneity is time- and labour-intensive and adaptive treatment is location-specific. One of such intrinsic limitations is incompleteness in comprehension of long-term heavy metal behaviour and remediation products[29]. Though most of the remediation treatments are short-term effective, secondary pollution hazard or risk are of highest priority recontamination. For example, metal retained in plants or microbes can again gain access to the environment if their biomass is discharged nonselective during bioremediation. Likewise, use of chemical substances or nanomaterials will lead to unintended consequences, i.e. the creation of harmful waste products or residual material in an ecosystem[30].

Toxicity and environmental stress from new and advanced materials like nanomaterials are actually a cause for concern. Even though nanotechnology has been very promising as far as the degradation of heavy metals is concerned, the issue of the risk factor of synthesis, use, and disposal of nanomaterials can not be ignored. During laboratory experiments, it was found that some nanomaterials have been reported to be harmful to aquatic organisms, soil, and even human health if they accumulate in the environment or added to the food chain. New cleaner and more efficient synthesis technologies, or so-called green nanotechnology, must be researched and invented to avoid or reduce such risks[31].

Mass application of new innovative remediation technologies is also plagued by huge economic limitations. Most of the recent technologies like those involving nanomaterials, electrochemical treatment, or genetically modified microbes are extremely expensive in terms of research inputs, piloting, and ultimate application. Due to being a costly product, high power requirements, and need of high-technology equipment to employ, it may restrict adoption, especially for developing countries. System maintenance and repairs will make it too expensive and thus such technology can not be affordable to small industries and developing countries[32].

The second is field practicability and scalability of some new methods. While laboratory testing is of high quality, it is not always feasible to implement these findings in utilising it in the field simultaneously. Stock availability problems for feeding, long-term system stability in the field, and technology scaling logistics tend to dampen the process. Phytoremediation, for example, is not expensive and environmentally friendly technology but not feasible to implement on a large scale since plants grow slowly and occupy enormous spatial area.

The policy and regulatory environment are also not conducive to investment in the application of cutting-edge heavy metal destruction technology. The scientists and industry are being cautious in most countries due to the lack of definition or standard for application of high-technology products like nanomaterials or genetically modified organisms. It is also not conducive to investment in cleaner technology for sterilisation without any subsidy or incentive to apply greener technologies[33].



	Scientific & Technological	Economic	Field Practicability & Scalability	Policy & Regulatory Constraints
Percentage (%)	30	25	20	15
Cases Reported	300	250	200	150

Percentage (%) Cases Reported

Fig. 3. Challenges in heavy metal degradation technologies

Finally, social acceptance and awareness must first come into effect before the installation of heavy metal breakdown technology to its full potential. Lack of information on the risk and benefit of using such a process will be sure to be met with resistance or suspicion by different groups and stakeholders in the region where such an operation is about to be carried out. For instance, the application of genetically modified organisms (GMOs) in biodegradation has been resisted strongly on ethical grounds, environmental impacts, and risk factors[34].

Heavy metal degradation evolution overall has gone a long way but is by no means without its flaws and obstacles. These have to be dealt with under a multidisciplinary approach of scientific facts, cost-effectiveness, eco-balance, and mass involvement. Through interdisciplinary collaboration, R&D expenditures, and facilitatory policy of regulation, it would be easier to bridge gaps and allow room for better and sustainable processes[35]. Challenges in heavy metal degradation technologies are shown in Fig. 3.

CONCLUSIONS

Future heavy metal degradation entails adopting innovative, sustainable, and multidisciplinary approaches to fight contamination more efficiently. Future technologies in the sector will depend on adopting advanced technologies and creating green solutions that are adaptable enough to fit in with strict environmental conditions. Some of the most promising research areas and future directions outlined below hold the potential to revolutionise the face of heavy metal degradation[36]. One of the key research fields is green and sustainable technology development. Bio-materials including biochar, algal biomass, and plant-derived biosorbents are environmentally benign options with lesser impacts on the environment. Optimisation of modification processes for biochar and other materials will further increase their effectiveness in adsorption to be used for treatment of more heavy metal types. Utilising renewable sources of energy, i.e. sunlight or microbial fuel cells, in the remediation system is a significant step towards conserving energy and sustaining the process. Nanotechnology will remain a force of revolution in the industry. Synthesis science of cost-effective, environmentally friendly, and biodegradable nanomaterials is the key to tackling the issue of environmental toxicity as well as scalability challenges. Green nanotechnology underpinned by plant- or microbial-based processes for nanoparticle synthesis holds especially promising potential[37]. Hybrid nanomaterials bearing properties of materials such as metal-organic frameworks (MOFs) and graphene oxide hold great potential to yield highly effective and selective heavy metal remediation technologies. The potential for integration of machine learning (ML) and artificial intelligence (AI) is an interesting and emerging front. AI-powered models and algorithms can justify remediation processes by surveying the patterns of contamination, forecasting the result, and tracking progress in real time. Integrated with Internet of Things (IoT) sensors and actuators, these applications would make adaptive, remote control of remediation possible with maximum efficiency and minimum cost of operations[38].

Genetic engineering and biotechnology progress is no less promising. Through the development of more tolerant and accumulative heavy metals by microorganisms and higher plants, phytoremediation and bioremediation would be unusually efficient. Additionally, studies on microbial consortia—synergistically active groups of microorganisms—can increase rates of degradation and cleanup of complicated-metal contamination scenarios. Ultimately, it will be interdisciplinarity that dominates. Combining knowledge from chemistry, biology, engineering, and data science will generate hybrid innovations that solve technological, environmental, and social issues. Facilitating public awareness and influencing beneficial regulation mechanisms will ensure effective deployment of such innovations, leading to a cleaner, healthier future. Such a vision of the future necessitates possible path-breaking enhancement of heavy metal remediation, leading to innovation towards world sustainability[39]. Nanotechnology has emerged as a promising field for the development of advanced materials with exceptional properties and diverse applications. Among these materials, metal oxide nanoparticles have drawn the most interest because of their fascinating optical, chemical, mechanical, electrical, biological, and magnetic properties[40].

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