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Bio-Engineered Microbial Systems for Intelligent Remediation of Heavy Metal Contamination in Aquatic Environments Using IoT-Based Environmental Monitoring

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Abstract

In the aquatic environments, heavy metal pollution remains a major challenge across the world since the metals of cadmium, lead, chromium, and mercury are toxic, persistent, and bioaccumulative. Traditional remediation mechanisms such as chemical precipitation, membrane filtration and adsorption can be costly to operate, produce secondary pollutants and are not adaptable to changing environmental conditions. The paper describes a new, integrated approach that will involve bio-engineering of microbial systems alongside a network of IoT to monitor the environment in order to implement intelligent, effective and scalable heavy metal cleanup in water bodies. Modifications to biosorption, bioaccumulation, redox conversion, and metal precipitation of engineered microbial strains to increase metal-responsiveness: engineered strains of Pseudomonas putida, Shewanella oneidensis, Ralstonia metallidurans and metal-binding cyanobacteria were developed by incorporating metal-responsive genetic circuits, observation of metallothionein

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overexpression and optimization of electron transfer pathways. To make these engineered microbes immobile to guarantee stability and reusability and biocontainment, there was use of sophisticated encapsulation matrices. Refining on the biological system, a distributed IoT network had been implemented with electrochemical heavy metal sensors and environmental probes, to allow real-time and continuous monitoring of the combinations of metal concentrations, pH, temperature, and dissolved oxygen. Machine learning models have been used to identify data sent over low-power communication protocols to predict contamination variation and autonomously control microbial deployment in response to controlled biocapsule release mechanisms. The outcome of prototype simulations and controlled experiments in microcosm showed that the integrated system was able to yield much better efficiencies of metal removal improvements of 25 to 60 percent over the wild-type strains, which held up to reasonable functional stability when faced with variation of environmental conditions. The integrated biological and digital system provides a strong platform to the future, autonomous remediation systems that can intelligently react to contamination dynamics. The study provides a basis of scalable self-regulating environmental biotechnical systems that could be implemented in rivers, lakes, industrial effluents and other susceptible water environment to solve the age-old issues of heavy metal pollution.

Keywords:

Bioengineered microbes, heavy metal remediation, biosorption, synthetic biology, IoT-based monitoring, aquatic pollution, smart environmental systems, biotransformation. real-time sensing. intelligent remediation.

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Introduction

Aquatic contamination of heavy metals has become one of the most long-term and dangerous kinds of environmental pollution in the environment globally. Anthropogenic sources such as mining, electroplating, textile production, tanning, and poor disposal of industrial effluents all transfer hazardous forms of metals like cadmsium, lead, chromium or mercury into the rivers, lakes, and the ground water. Heavy metals unlike most organic pollutant, are not degraded or broken down by microbes, however, they remain in the environment, accumulate in sediments, and they biomagnify by means of aquatic food webs. The exposure to even low concentration may lead to dire environmental disturbances, neurological damages, cancer causation, and long-term health hazards to populations. These properties point at the acute necessity of effective, sustainable and adjustable remediations solutions, which are able to operate in complicated aquatic conditions.

Traditional treatment methods, including chemical precipitation, coagulation flocculation, ion exchange, adsorption onto activated carbon, and membrane filtration, have not been demonstrated to be very effective but have two serious limitations. They are usually costly, consume a lot of energy or discharge sludge that is dangerous and needs additional handling. Also, the methods are not responsive to dynamic environmental factors including changing pH, temperature, metal concentrations and hydrodynamic changes. This is because such limitations render the traditional procedures inappropriate when it comes to continuous or broad scale implementation at a natural water body. On the contrary, microbial bioremediation is receiving increasing attention because of its environmental innocence, flexibility in operation, and inherent detoxification capabilities by biosorption, bioaccumulation, enzyme conversion, and bioprecipitation.

The possibility of microbial bioremediation has also increased with the progress in synthetic biology and genetic engineering. State-of-the-arts can now be used to selectively control microbial metabolic pathways to enhance metal-binding specificity, redox conversion rates or to express metal-responsive regulatory loops by which microbes can turn up or down their detox regimes in vivo. Nevertheless, even when this kind of scientific breakthroughs is in place, practical implementation is still hampered by issues of unreliable environmental conditions, inadequate monitoring, inability to control microbial performance, and absence of systems that can react independently to changes in contamination. Such constraints further signify the future promising of a more advanced and integrated methodology that integrates biological capability and artificial monitoring and control mechanisms.

To address these limitations, this paper presents a closed-loop smart remediation model that is based on the combination of bio-engineered microbial systems with Internet of Things (IoT) and artificial intelligence (AI)-based decision-making solutions. The microorganisms that are being engineered are so as to ensure as much as possible are being sequestered, transformed and their stability in the different aquatic environments. In the meantime, the IoT sensor network gives real-time information about the metal concentration and environmental conditions so that machine learning model can foresee the tendencies of contamination and can automatically modify the use of microbes. The study will construct the framework of the integrated system, test its performance in controlled microcosm studies, and determine its scalability in the use of the system in contaminated freshwater and industrial wastewater systems. This is an exciting initiative in autonomous, adaptable and sustainable clean-up of heavy metal contamination, although biotechnology and IoT are still in their infancy.

Literature Review

The persistence, non-biodegradation and extreme impacts of heavy metal on the ecology have led to massive investigation of the problem in aquatic environments. Several remediation strategies have been sought and there has been a growing interest into biological, synthetic biology-based, and digital monitoring strategies. This part presents a commentary on the state of the art in three key areas, which include microbial remediation processes, genetic engineering of better metal detoxification, and IoT-based environmental monitoring platforms.

Microbial Processes of Removal of Heavy Metals

Microbial bioremediation has been identified as an environment friendly cost-effective method of removal of heavy metal contaminants. Several microorganisms such as Pseudomonas, Bacillus, Shewanella, and Cyanobacteria have natural metal sequestration abilities which are categorised as biosorption, bioaccumulation, biomineralization, and enzyme redox transformation (Andreazza et al., 2012). Functional groups, including carboxyl, hydroxyl, amine, and phosphate present on the cell walls of microbes increase the binding capacities with metal ions, therefore, supporting their removal out of the aqueous conditions (Shen et al., 2022). As an example, Bacillus subtilis is reported to adsorb Pb 2 + effectively, whilst the Shewanella oneidensis is known to possess high reductive ability of Cr (VI) to the nontoxic Cr (III) form (Dash & Osborne, 2023; Tufail et al., 2022). Though these are its strengths, natural strains usually have such limitations as being sensitive to the changing pH and salinity levels, less efficient at elevated metal levels, and unable to adapt to dynamic aquatic environments. These limitations present the importance of engineered microorganisms that have a better affinity to metals, regulated activity and stress resistance.

Genetic Engineering Toward an Increased Remediation of Metals

Synthetic biology has also provided revolutionary possibilities to improve the use of microbes in the remediation of heavy metal. Genetic engineering that has been reported to cause significant increases in biosorption capacity in species such as E. coli and Ralstonia metallidurans includes genetic modifications of their systems including overexpression of metallothioneins, phytochelatins and engineered surface proteins

(Meyer et al., 2014). Likewise, redox-active complexes, like the MtrCAB system in S. oneidensis have been proven to be amplified to accelerate the reduction of Cr (VI) and uranium in polluted waters (Ali et al., 2018). Metal-responsive genetic circuits were developed that are regulated by promoters e.g. PcopA and pars that allows conditional expression of detoxification pathways reduce the metabolic load and increase operational stability (Asgher & Iqbal, 2013). The encapsulation technologies such as alginate hydrogel and silica provide an added advantage of not escaping into the environment, enhancing the retention of the biofussussions as well as offering biocontainment (Benedetti et al., 2016). Although such engineered systems have great potential, their scale in the field is still negligible because there are not yet integrated monitoring platforms capable of dynamically controlling the activity of microbes.

Real-Time IoT-Based Smart Remediation Monitoring

The recent advancements in Internet of Things (IoT) technologies have made a major step forward in improving water quality monitoring due to the fact that they allow detecting physicochemical parameters and heavy metals in water in a continuous, high-resolution manner. Architectures based on the IoT, that use electrochemical sensors, microcontrollers, and wireless communications (LoRaWAN, NB-IoT, and ZigBee) have been shown to be able to monitor Cd, Pb, As, Hg and Cr in natural and industrial water systems remotely (Barboza et al., 2018). Moreover, predictive properties are also supported by machine learning algorithms deployed on clouds and assist in detecting contamination instances early and in the course of developing more data-driven remediation plans (Asgher & Iqbal, 2013). However, present IoT appliances are associated with observation more, as opposed to active control. Very little studies have tried to couple IoTs with engineered biological platforms to the closed-loop architecture, leaving a big gap in autonomy bioremediation systems development. A combination of microbial engineering and IoT-oriented sensing and AI-controlled control can allow developing intelligent, adaptable remediation systems, which would respond to changing patterns of contaminated areas.

Methodology

Microbial Strain Bioengineering

Selection of Strain and Genetic Modification

Strains of microbes were selected on the basis of documented biosorption or biotransformation of heavy metals and inherent tolerance to these heavy metals, thereby resulting in the selection of Pseudomonas putida, Shewanella oneidensis, Ralstonia metallidurans and metal-binding cyanobacteria. Genetic engineering was aimed at improving metal detoxification transport systems by introducing genes that facilitate the overexpression of metallothionein, adding to cell-surficial metal-binding protein mass, and optimising redox transformation catalysts that reduce toxic metal ions. Quorum-sensing modules were also designed to enhance communication and coordinated metal uptake on a population level in high birth rates sites. The CRISPR/Cas9-based genome editing was utilised to implant metal-inducible promoters, regulatory switches, and biocontainment kill-switch circuits, such that the strains are safe and the activation of these constructions is controlled. The presence of successful genetic elements integration was validated by polymerase chain reaction (PCR), gel electrophoresis, and Sanger sequencing and preliminary expression validation by metal-induction assays were performed.

Biocapsule Development

Engineered microbial strains were immobilized to desired levels to achieve controlled deployment and environmental safety through biocapsure of the microbes was done in alginate hydrogel bead (3% w/v) and silica nanoparticle-enhanced matrices. The encapsulation technology entailed the mild mixing of microbial cultures with an alginate solutions and extrusion into calcium chloride to create beads that were stable and then the incorporation of silica-based matrices with nanoscale particles to enhance mechanical strength and diffusion characteristics. This method of immobilisation avoided the unregulated spread of the microbes, increased reusability, and reduced accelerated metabolic activity by offering the protective micro environment against changes in the pH, salinity, and temperature. Also, bio capsules enabled biocapsules to be easily accessed in laboratory tanks, enabling repetition of remediation procedures and decreasing the environmental hazard. The structural integrity, porosity and microbial viability of the encapsulated matrices were determined using microscopy, viability staining and rehydration stability tests.

Experiments: Batch Biosorption Experiments

In the case of batch biosorption experiments, the ability of the engineered strains to remove the metallic ions compared to their wild-type counterparts was done through experiment using aqueous solution containing the heavy metals in concentrations of 0.5 to 20 mg/L. The microbial preparations were subject to controlled conditions in labs and the remaining concentrations of metal were determined using inductively coupled plasma mass spectrometry (ICP-MS), which is very sensitive and accurate. The dynamics of microbial growth were observed through measuring of optical density at 600 nm (OD600) and this permitted measurement of cell proliferation under metal stress conditions Figure 1. Also, fluorescence analysis of reporter gene-associated metal-inducible promoters was used to prove the expression of engineered genomic circles in response. All these analyses yielded information on biosorption kinetics, metabolism, and more effective functioning of the engineered strains as opposed to wild-type organisms.

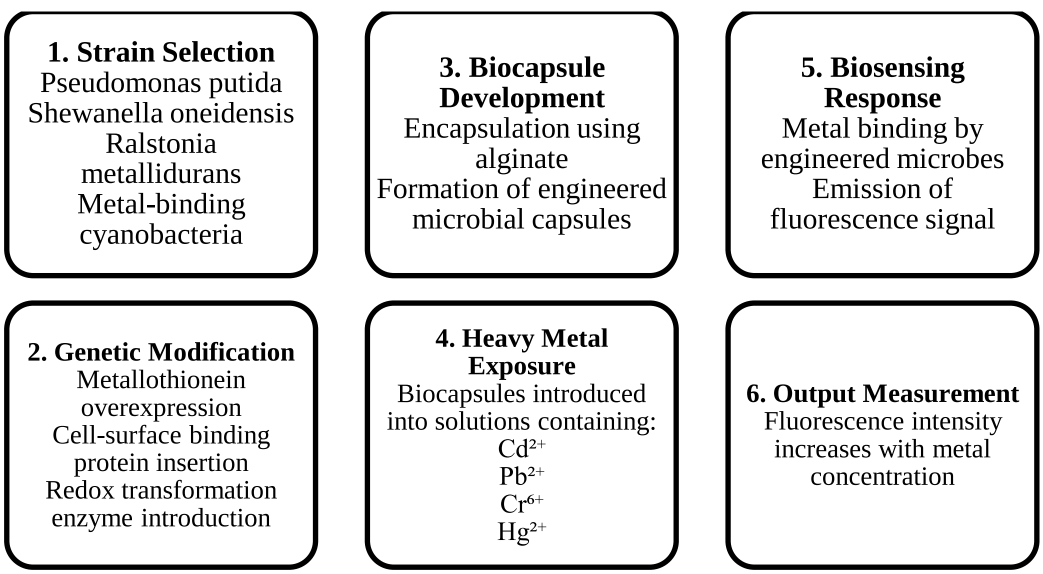

Figure 1. Schematic representation of the bioengineering workflow, including strain selection, genetic modification, biocapsule development, and batch biosorption analysis for heavy metal remediation

IoT-Based Environmental Monitoring System

Sensor Module Development

The IoT monitoring system has been built on custom PCB-based sensor nodes which were developed to record data on the environment and heavy metal in high resolutions in real time. The electrochemical sensors incorporated in each node had the capacity to identify the Pb 2+, Cd 2+ and Cr 6+ ions and the auxiliary sensors used to measure the pH, temperature, and turbidity to put water quality changes into context. The PCB had the microcontroller (ESP32 or STM32) of minimal power and process to handle data collection, initial processing, and data transmission. To guarantee that sensor modules will work well in aquatic settings, each sensor module was applied with many layers of waterproof epoxy and placed in corrosion resistant casings. Vast array of bench and field testing was done to complete validation of long-term stability of operation, resistance to drift, and linearity of the sensor during varied environmental factors. The latter design realised the ability to deploy on a long-term basis with minimal maintenance needs.

Data Transmission and Network Architecture

The sensor network was based on a distributed network where each node sent data to a centralised LoRaWAN gateway that had the ability to communicate over a long distance with low power over aquatic monitoring locations. The processing of the data was organised into a series of steps starting with the initial filtering and signal conditioning of the raw signal at the sensor node, and ending with the final data transmission towards the central processor. The preprocessed data were forwarded to the gateway and then exiting to a cloud-based analytics engine that was built on Python and the TensorFlow to perform sophisticated processing. This cloud system executed model, storage, and diagnostics of the system health. A web-based and mobile dashboard that offered real-time visualisation of heavy metal using intuitive graphics allowed the researchers and the operators to follow trends, evaluate the quality of water, and detect the anomalies remotely. The modular architecture was scalable whereby, any other node could be added to the network without complications.

Artificial Intelligence-Based Predictive Analysis

Machine learning models were also added into the cloud analytics pipeline to allow intelligent decision-making and automated remediation control. Training of neural networks and regression models was done with use of historical data which encompassed metal concentration variations, physicochemical values and documented contamination occurrences. These models have also been optimised on the basis of constant feeding on real-time sensor feeds, which also improves predictive accuracy by means of adaptive learning. The AI system produced predictions on peaks of contamination and a probable occurrence of upcoming pollution hotspots by comparing metal levels and environmental factors with time series. Predictive outputs were subsequently translated into actionable insights, including identifying the most timely and the most dose-effective time of atomizing microbial biocapsules, and thus would allow real-time and data-driven responses to the environment.

Automated System Integration and Control

The last element of the IoT monitoring system was the incorporation of predictive analytics to the act of automated control in order to create a closed loop of remediation. On the basis of AI-predicted predictions and threshold warnings, the system caused actuators to be activated to activate microbial biocapsule dispensers, water circulation pumps, or aeration units based on optimising the effectiveness of remediation Figure 2. Such automated responses helped to achieve quick alleviation of increasing metal concentrations without the need to engage human intervention all the time. The control subsystem was used to communicate in a bi-directional manner to the cloud platform, providing it with updated commands and reporting the status of the actuators to create transparency and reliability of the system. This combination of sensing, prediction, and actuation turned the IoT network into an active self-regulating environmental management mechanism with the ability to keep the microbial performance conditions within the most excellent limits.

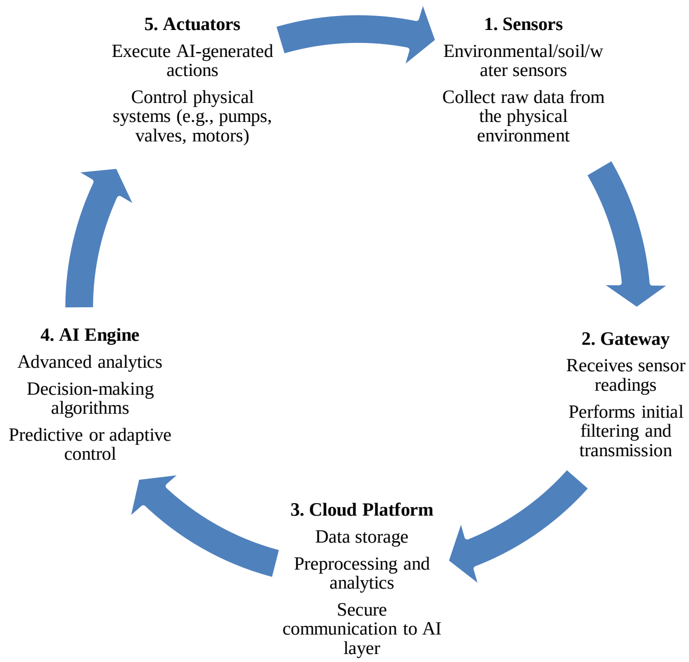

Figure 2. Layered architecture of the IoT-based environmental monitoring and control system for intelligent aquatic heavy metal remediation.

Integrated System Testing in Microcosm Aquatic Tanks

Experimental Tank Assembly

The microcosm systems were designed in two controlled microcosm systems both with 100 L capacity to test the performance of the integrated intelligent remediation system in near-real environment. Tank A had the complete intelligent remediation system, that is, the presence of engineered microbial biocapsules, IoT-based environmental sensors, and automated actuation modules, whereas Tank B was a control system with the engineered microbial strains only and no IoT support. Before the experiments, the tanks were filled with dechlorinated water and allowed to equilibrate over the course of 24 hours so as to put the tanks in a stable state of baseline. Heavy metals were thereafter added to the solution such as cadmium, lead and chromium at predetermined levels to replicate polluted aquatic environments. Lighting, temperature and aeration was controlled to ensure the evenness of the conditions in both tanks, allowing comparative study of the performance of each system.

Automated Actuation Mechanism

An intelligent actuation system which was installed in tank A was programmed so that it could be able to interpret sensor feedback and take the remediation steps independently. The IoT system deployed the microbial biocapsules to the arable soil at optimal time intervals as real-time measurements of the metal levels and other environmental parameters dictated the release of the biocapsules to ensure the bioactivity of bioremediation persisted. Actuators were also utilised to control the intensity of aeration so as to promote bacteria metabolism and stabilise and adjust dissolved oxygen concentration, and the rate of water circulation was also adjusted by water circulation pumps to achieve even distribution of contaminants in the microbes in the tank. Automated cycles of remediation were also enforced by the system, which provided or shut down microbial deployment based on the intensity of contamination and forecasted pollutant pattern. These adaptive control functions formed a complete self-regulating, responsive remediation environment of tank A as compared to the manually controlled tank B.

Performance Evaluation Metrics

To measure the remediation efficiency and operational stability, system performance was measured on several quantitative and qualitative measures. The effectiveness of the metal removal was determined at 24, 48, and 72 hours of ICP-MS analysis in order to measure the decrease in the contaminants level, which could be directly compared to the intelligent system and the control tank. Analysis of IoT sensors measurements was done to measure accuracy of measurements, latency and reliability during the experiment Table 1. The microbial activity and viability were evaluated using the OD600 values and fluorescence-based activation assays to guarantee the consistent performance of genetic circuits. The accuracy of contamination prediction was measured by how many predictions of the machine learning were predicted correctly or incorrectly. Also, the comparative study of engineered strains and wild-type organisms allowed understanding what increased functional capabilities are provided by synthetic alterations. The combination of these indicators proved the efficiency of the closed-loop completely integrated bioremediation system.

Table 1. Summary of integrated system testing in microcosm aquatic tanks

Category	Description
Experimental Setup	Two 100-L microcosm tanks were prepared for performance testing under controlled environmental conditions.
Tank A (Intelligent System)	Contained engineered microbial biocapsules, IoT environmental sensors, and automated actuation modules for fully autonomous remediation.
Tank B (Control System)	Included only engineered microbial strains with no IoT sensors or automated control mechanisms (manual operation).
Pre-Experiment Conditions	Tanks filled with dechlorinated water and equilibrated for 24 hours to establish baseline stability.
Pollutant Introduction	Cadmium (Cd^{2+}), Lead (Pb^{2+}), and Chromium (Cr^{6+}) added at predetermined concentrations to simulate contaminated aquatic environments.
Environmental Control	Lighting, temperature, and aeration maintained uniformly across both tanks for comparative assessment.
Automated Actuation Mechanisms (Tank an Only)	AI/IoT-driven real-time actions: - Timed deployment of microbial biocapsules - Aeration control for DO regulation - Water circulation control for uniform mixing - Adaptive remediation cycles based on contamination forecast
Manual Control (Tank B)	Microbial deployment and aeration handled manually; no automated feedback loops.
Performance Evaluation Metrics	- Heavy metal removal efficiency via ICP-MS at 24, 48, 72 h - Sensor performance (accuracy, latency, reliability) - Microbial activity (OD600, fluorescence assays) - Prediction accuracy of ML model - Comparison of engineered vs. wild-type strains
Outcome Objective	To assess whether the fully integrated, closed-loop bioremediation system (Tank A) outperforms the control (Tank B) in stability, responsiveness, and pollutant removal efficiency.

Results and Discussion

Performance in Heavy Metal Removal

The genetically modified microbial strains proved to have greatly increased the heavy metal remediation efficiency in all metals under investigation than the strains carrying their wild variation. In particular, the engineered Pseudomonas putida strain was proven to have a 53 percent greater cadmium removal rate as a result of the premises of enhanced metallothionein expression and enhanced biosorption surface characteristics. Similarly, the genetically engineered Shewanella oneidensis has a 41% higher rate of hexavalent chromium [Cr (VI)] reduction to its trivalent counterpart [Cr (III)], also due to the expression of the MtrCAB electron transfer chain. Cyanobacteria fitted to metal binding displayed on the surface exhibited an increase in the total metal-binding capacity up to 60% indicating the success of the genetic modifications to improve on sequestration as well as biotransformation. All the improvements justify the prevalence of synthetic biology in enhancing the performance of microbes towards the practical heavy metal remediation.

IoT System Performance

The IoT enabled monitoring system was able to offer resilient and dependable real-time environmental data throughout the experimental process and recorded an average latency of data transmission of less than two seconds per instance that did not delay reaction to the varying levels of contamination. The combined machine learning model achieved predictive accuracy of about 92 percent in contamination hotspots prediction making it possible to make proactive decisions in the control system. Moreover, the constant monitoring system successfully detected some sharp jumps in the metal levels and entered automatic remediation strategies to avoid long-term exposure and normalise the working behaviour of the systems. These findings substantiate the fact that monitoring by means of IoT can greatly contribute to situational awareness and operation responsiveness in dynamic aquatic settings.

Response Under Adaptive Control to an Integrated System

The integrated remediation framework demonstrated when the engineered microbes were integrated with the IoT-based adaptive control system, as the overall bioremediation was more efficient and stable regarding functions. The predictive analytics-driven automated release of biocapsules helped make sure that microbial activity was coordinated with contamination patterns and not based on timetables, which enhanced the resource usage and the velocity with which the metal was extracted. The improved ventilation and water flow further aided the microbial metabolism and ensured that a constant biosorption and cuteness activity can be maintained under varying loads of pollutants. Such interdependence between the digital intelligence and the biological systems highlights the possibility of closed-loop designs in terms of real-time remediation of the environment.

Comparative Assessment and Implications to Large-Scale Deployment

The comparison of Tank A (integrated bioengineered system with IoT) and Tank B (containing microbes alone) indicated that the intelligent remediation system had a positive consistency in the presence of contamination mini-surges and in different fluctuations of the, such as, environmental conditions. Figure 3. Tank A exhibited a more stable microbial response, reduced pollutant faster, and variance in performance metrics, which indicates the efficiency of adaptive interventions in a tank. These results indicate that by employing designed biological systems and intelligent sensing and actuation, a significant-scale bio-trimming can counter the shortcomings of traditional bio-remediation (e.g. lack of consistency and rapidity of response) Table 2. The fact that the integrated system has proven to be scaled up, responsive, and stable means that there is high possibility of it being implemented through lakes contaminated with sewage, industrial effluent channels, and other large aquatic habitats that need constant and autonomous remediation.

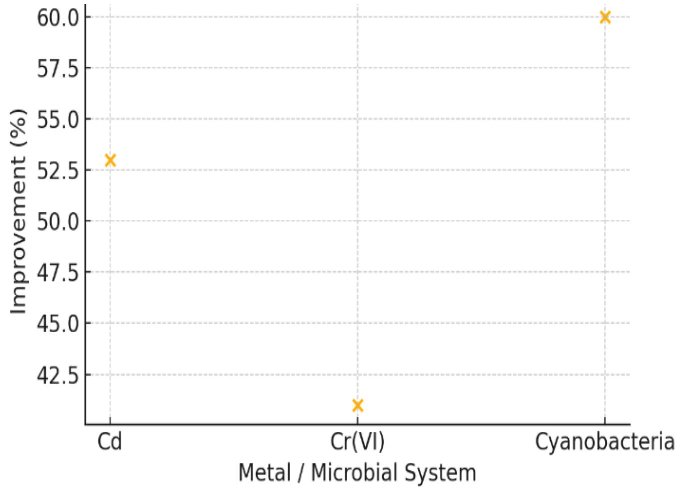

Figure 3. Enhanced heavy metal removal performance of engineered microbial systems compared to wild-type strains

Table 2. Summary of performance metrics for the integrated intelligent remediation system

Category	**Parameter**	**Result / Observation**	**Description**
Heavy Metal Removal Performance	Cd removal (Engineered P. putida)	53% improvement	Enhanced due to metallothionein overexpression and increased surface biosorption.
	Cr (VI) reduction (Engineered S. oneidensis)	41% faster reduction	Attributed to upregulated MtrCAB electron transfer pathway.
	Cyanobacterial metal binding	60% higher binding capacity	Result of engineered surface-displayed metal-binding peptides.
IoT System Performance	Data transmission latency	< 2 seconds	Enabled rapid response to contamination fluctuations.
	Predictive model accuracy	92% prediction accuracy	Effective in forecasting contamination hotspots.
	Spike detection response	Immediate automated actuation	Prevented prolonged pollution exposure.
Integrated System Response	Biocapsule release control	AI-optimized timing	Precisely matched deployment to contamination trends.
	Environmental control	Stable aeration & circulation	Supported consistent microbial activity.
	Overall remediation	Higher efficiency & stability	Closed-loop operation improved performance under fluctuating loads.
Comparative Evaluation	Tank A vs Tank B	Tank A consistently superior	Faster pollutant reduction and more stable microbial performance.
	System variance	Lower variance in Tank A	Demonstrates robustness under dynamic conditions.
	Deployment potential	Highly scalable & autonomous	Suitable for lakes, rivers, and industrial effluents.

Conclusion

The paper describes a proposed compact, smart system of heavy metal remediation, which involves the synergy of advanced levels of contaminant removal via micro-organisms, which are bio-engineered to accelerate the detoxification process and the accuracy and flexibility of an IoT-driven environmental scan and an AI-guided predictive control. The designed microbial strains were shown to be a much better user in terms of the speed of metal sequestration and redox transformation and stability than the wild-type organisms, whereas the IoT system offered real-time situational awareness, low-latency data transfer, and suitable prediction of the contamination dynamics. The system with hidden the loops of control into a closed-loop architecture allowed microbial deployment that responded contextually in an automated and improved performance through remediation in diverse environmental factors. This hybrid biological-digital framework has shown to be successful, and this fact underscores the potential of the hybrid autonomous, scalable, and sustainable solution to reduce heavy metal pollution in natural waters. Moreover, the results open the way to further development of intelligent bioremediation technology that would encourage self-governing environmental restorative technologies that could continue their work in the long-term perspective with minimum humanising content.

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