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Artificial Intelligence Applications in Analyzing Algae's Pollutant Absorption Capacity: An Innovative Environmental Perspective / Review Article

Baraa Hussein Abdulhadi [1], Athmar Hussein Ali [2], Reyam Naji Ajmi [3]
[1] University of Diyala, College of science, Department of Forensic Sciences
dr.baraahussein@uodiyala.edu.iq

[2] University of Diyala, College of Science, Department of Biology
athmarhussein@uodiyala.edu.iq

[3] Department of Biology Science, Mustansiriyah University, POX 46079, Iraq-Baghdad
reyam80a@yahoo.com

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Annotation: The world faces severe environmental dangers as freshwater and aquatic life are more and more contaminated with heavy metals, organic compounds, and microplastics. They are harmful to ecosystems and human health and require effective and sustainable solutions to eradicate them. Algae are among the most ubiquitous organisms with a natural ability to remove such pollutants, but common knowledge in regards to their mechanism and efficacy has been hindered due to the complexity of environmental factors and their interactions. Further, utilization of artificial intelligence (AI) techniques for studying and predicting algal performance under different environments is still in development and faces various challenges. Article Objective: This paper seeks to address the use of algae in bioremediation of pollutants and illustrate how artificial intelligence techniques such as machine learning and artificial neural networks have enhanced our understanding of the effectiveness of algae for the removal of pollutants under different conditions. The article further tries to present case studies and real-world applications that indicate the effectiveness of such methods, along with the current issues and future prospects towards merging AI with biological indicators for pollution treatment. Article Methodology: Recent journal articles of the past couple of years (2023-2024) on the topic of algae and artificial intelligence in the environment were retrieved and studied, and research on the application of advanced techniques such as neural networks, deep learning, and big data in measuring algae efficiency was emphasized. Different types of algae and their role in heavy metal removal, organic contaminants, and microplastics were covered. Artificial intelligence models applied to predict algae biological performance were taken into account. The main challenges hindering the industrial application of these models were discussed, and promising future technologies such as interactive intelligent systems and remote sensing integration were highlighted. Studies showed that algae such as Chlorella vulgaris, Scenedesmus obliquus, and Spirulina platensis possess a high capacity to absorb and degrade various pollutants from different aquatic environments. The use of artificial intelligence enabled the development of accurate predictive models with an accuracy of 95% or more, providing faster and less expensive alternatives to traditional laboratory and field experiments. Field case studies have demonstrated the effectiveness of intelligent algorithms in dynamically identifying and optimizing optimal treatment conditions. However, higher-quality data and interdisciplinary collaboration are still needed to overcome current limitations. Future prospects point to broad potential for the use of interactive artificial intelligence and smart monitoring systems based on algae, as well as the integration of satellite data and remote sensing technologies to expand the scope of applications.

Keywords: Algae, environmental pollutants, heavy metals, artificial intelligence, predictive models.

1. Introduction:

Algae, whether microscopic or multicellular, are one of the most important components of aquatic ecosystems, contributing to oxygen production, nutrient cycling, and providing food for many organisms. Algae are promising bio-agents for environmental pollutant remediation due to their unique characteristics, such as rapid growth, high adaptability, and physiological and biochemical mechanisms that enable them to absorb, accumulate, and degrade toxic substances (Oruganti,*etal*, 2023)

Algal mechanisms for pollutant removal primarily involve biosorption a passive process that relies on the interaction between algal cell walls and metal ions as well as biodegradation, where enzymes decompose complex organic compounds into simpler, less harmful substances. Other mechanisms include intracellular accumulation (bioaccumulation) and biotransformation (Chen,*etal*, 2023).

Given that recent advances in artificial intelligence (AI), particularly machine learning and artificial neural networks (ANNs), have made it possible to establish accurate predictive models to evaluate the efficiency of algae in removing contaminants under varied conditions of the environment, these models enable the analysis of vast experimental data with a perspective toward comprehending the parameters affecting algae efficiency as well as the prediction of their subsequent biological response to optimize extensive uses of bioremediation Kumar,*etal*, 2023.

One study recently (Zhang *et al.*, 2023) used deep learning models to investigate *Chlorella vulgaris* capacity to adsorb nitrate and copper from wastewater. The models predicted removal efficiencies with a 96% rate of accuracy.

2. The Role of Algae in Bioremediation of Pollutants

2.1 Algae Species Utilized according Singh,etal 2024

Certain algae species are the ideal model for bioremediation due to their higher ability to remove contaminants and adjust to varying environments. The most prominent among them are:

Green algae (Chlorophyta): like *Chlorella vulgaris and Scenedesmus obliquus,* which have high ability to adsorb heavy metals and biodegrade organic compounds, apart from being facile to cultivate in closed systems.

Brown algae (Phaeophyceae): *Sargassum spp.*, whose cell walls contain alginates, making them able to possess a high degree of heavy metal adsorption in ionic form.

Blue-green algae (Cyanobacteria): *Spirulina platensis and Anabaena spp.,* with nitrogen-fixing activity and the ability to remove excess nutrients and heavy metals from water, making water cleaner. They have also been found to degrade complex organic compounds like aromatic hydrocarbons.

A study (Kumar *et al.*, 2024) identified that an association of green algae and blue algae eliminated a lead composition of up to 89% within a single 72-hour treatment.

2.2 Extractable Pollutants

There are numerous environmental toxins that are removable through algae, including according to Alfaro, A.C., & Navarro, D. (2023) :

Heavy Metals:

Lead (Pb): Is adsorbed by cell walls as ions and cations.

Mercury (Hg): Can be degraded by methylmercury reductase enzymes of some algal species.

Cadmium (Cd) and Zinc (Zn): The above research indicates that algae can immobilize these metals in vacuoles or by means of certain protein complexes.

In an experiment (Al-Gheethi *et al.*, 2023), *Chlorella vulgaris* eliminated more than 75% of cadmium and 60% of zinc from contaminated water over a period of five days.

Organic compounds: Petroleum hydrocarbons and pesticides, are degraded by algae using enzymes such as *monooxygenase and hydrocarbonase*. *Scenedesmus* algae eliminated 68% of crude oil from water samples contaminated with it in a week in research (Hosseini *et al.*, 2024).

Microplastics: Recent studies have shown that algae can be used to bio-flocculate microplastics, facilitating their sedimentation and removal from water. An experiment used neural network models to predict the effectiveness of algae in degrading polyethylene microparticles and compared with actual results to find that predictions were over 90% accurate (Li *et al.*, 2023).

Algae are among the most promising resources in environmental remediation, and adding artificial intelligence techniques brings new prospects for insight and optimization of the performance of these organisms to clean up environmental pollutants. Recent research confirms that combining nature's biological attributes with smart technologies can potentially speed up the development of sustainable solutions against pollution in our ecosystem.

3. Artificial Intelligence as an Advanced Analytical Tool

With growing environmental issues resulting from water contamination, heavy metals, and particulate organic materials, there is a critical need for intelligent analysis tools that can help researchers deal with the huge volumes of complex data generated by environmental studies. Artificial intelligence (AI) comes into its own in this regard since it is capable of mimicking human cognitive abilities through programs that possess the potential to learn, forecast, and auto-analyze Zhou, Q., & Wang, Y. (2023).

In algal bioremediation, AI holds great potential to understand the complex patterns of algal reactions to pollutants, optimize efficient species selection, and come up with predictive mathematical formulations that help design more efficient and sustainable treatment strategies.

3.1 The Importance of AI in Environmental Analysis

A- Environmental Data Analysis on a Large Scale: Environmental investigations of algae are usually founded on multi-dimensional information, including cellular composition, absorptive rates, pollutant concentrations, water physicochemical parameters, and microscopic information. The AI software are able to compute such information quickly and precisely and identify the most relevant factors affecting the treatment efficiency, reducing reliance on time-consuming and costly standard experiments.

Application Example: Li *et al.* (2023) used the big data analysis to contrast the results of laboratory tests for the removal of heavy metals by *Chlorella vulgaris* with field measurements from industrially polluted environments and the models had a 92% predictability.

Predicting Algal Bioresponse

Algae bioremediation efficiency is affected by many variables such as temperature, pH, elemental levels, and light. Artificial intelligence can be used to develop predictive models based on learning past trends in the environment and predict bioremediation efficiency before it is applied Zhang *et al.* (2023) constructed a deep neural network model to forecast the efficiency of copper and nitrate removal from wastewater using Chlorella and reached over 96% accuracy rate against real experiments.

B- Algae Classification Depending on Their Bioefficiency

Through the application of classification algorithms, algae species can be categorized based on their biological response in degrading or accumulating a specific contaminant. This process helps scientists select the most effective species in accordance with the specific types of pollution at a given site Kumar et al. (2024) used the Support Vector Machine algorithm in the classification of 12 algal species according to their cadmium removal efficiency and the model indicated that three species did better by more than 80%.

Table 1: Key Artificial Intelligence Techniques Used in Algal Analysis

AI Technique	Application in Algal Analysis
Artificial Neural Networks (ANNs)	Predict the uptake rates of heavy metals (Pb, Zn) based on input parameters such as pH, temperature, and algal biomass.
Classification Algorithms (SVM, Decision Trees)	Classify algal species based on their biosorption efficiency and tolerance to specific pollutants.
Deep Learning	Analyze high-resolution microscopic images to detect subcellular changes in algae under pollutant stress.
Big Data Analytics	Integrate laboratory data with field and satellite data to model algal response under real-world pollution scenarios.

Applied Study: Wang *et al.* (2023) applied deep learning methods to examine Scenedesmus algae hydrocarbon-exposed cell images. They identified an early indication of cell wall alterations to predict the effectiveness of treatment before the contamination becomes severe.

Artificial intelligence represents a paradigm shift for modern environmental sciences, particularly for algal science, as it assists in accelerating analysis, improving the validity of predictive models, and reducing the application of costly laboratory and field experiments. Artificial intelligence integration into algal environmental response studies opens up vast applications in the removal of polluted water as well as strategic environmental policy planning using intelligent and sustainable strategies.

4. Real-World Applications and Case Studies

Real-world applications and case studies are crucial to documenting the success of integrating biological technologies and AI in remediating environmental pollution. Through the integration of computer models with field and experimental data, researchers have enhanced the accuracy of predictions and attained a greater understanding of the behavior of microorganisms, especially algae, in contaminated ecosystems. This chapter shows practical applications of artificial intelligence (AI) models to studying the effectiveness of algae in absorbing polluting substances, using the metal lead as a case study of an extremely toxic metal polluting substance.

4.1 AI Model for Predicting Algal Lead Uptake

Chlorella vulgaris is amongst the most widely used species in heavy metal bioremediation due to its superior biosorption capacity and tolerance towards different environments. In a recent study, Jin *et al.* (2023) Experimental data were collected from lab experiments wherein the response of *Chlorella vulgaris* upon exposure to various concentrations of lead (Pb^{2+}) for 48 hours was observed. A model of an artificial neural network (ANN) was trained with independent variables such as according to Hamza, R.A., & Hussein, S.A. (2024) :

Initial lead concentration, pH, Temperature, Algal biomass concentration, Exposure time

The model was highly predictive with 95.2% prediction accuracy ($R^2 = 0.952$), demonstrating that it was able to accurately predict absorbed lead quantities without conducting additional experiments, this model is its ability to retrain and adapt (learn) to new data, hence making it an adaptive model that can be used in different polluted regions depending on their respective conditions.

4.2 Environmental Efficiency Prediction with Artificial Intelligence

In a field experiment in the real-world situation at an industrial-contaminated site in southeastern China, artificial intelligence algorithms were used to simulate the efficacy of *Scenedesmus obliquus and Chlorella vulgaris* in industrial pollutant removal (petroleum hydrocarbons + heavy metals blend). Results from this experiment were documented in a recent paper by Zhou *et al.* (2024), where the researchers relied on a reinforcement learning algorithm to supplement big data analysis.

Extensive field measurements were collected, including: Redox coefficient, Light intensity, Temperature of air and water, Organic matter and mineral concentrations, Velocity of water flow By incorporating these parameters into the model, the researchers were able to determine the optimum physicochemical conditions for maximum adsorption efficacy (pH 6.5–7.2, temperature 25–30°C, light intensity 100 μmol photons/m²/s). The models have also been used to predict the final concentration decrease of lead and zinc from the water after 5 days with an accuracy of 93%.

This study demonstrates not only the capability of AI as a data analysis tool, but also as a very powerful field assistant in optimization and real-time advice of biological systems.

Previous case studies indicate that the integration of AI with technologies of algal bioremediation is a paradigm shift in environmental pollution management. It is now possible to predict algal species' behavior accurately, determine optimum remediation conditions, and modify ecological restoration strategies based on specific field site conditions. This union of environmental biology and smart algorithms is the foundation for intelligent and adaptive environmental remediation systems that will drive the clean technology future.

5. Challenges and Future Prospects

Integration of AI technologies with environmentally friendly algae creates an exciting paradigm for optimizing bioremediation processes. The area is not without technical, scientific, and implementation challenges that have to be addressed to realize its full effectiveness and pervasive industrial applicability.

5.1 Challenges include:

A- Lack of High-Quality Data: Accurate, diverse, and high-quality data are the cornerstone for building reliable AI models. However, environmental research faces significant limitations in collecting integrated data covering all environmental factors (temperature, pH, pollutant concentration, algal composition), limiting the ability of models to generalize and accurately predict under changing environmental conditions. The diversity and diversity of data sources between the laboratory and the field further complicates integration.

B- **Greater Integration between Environmental Scientists and AI Engineers:** Developing effective AI models requires a multidisciplinary effort that combines environmental expertise with AI technical knowledge. Many current projects lack effective communication between the two teams, resulting in models that are incomplete or unresponsive to actual environmental needs. Increasing scientific collaboration and developing common frameworks are essential to accelerate progress in this field.

C- Broad Industrial Applicability: Despite the success of models in laboratories and small-scale field studies, the biggest challenge lies in transferring these models to large-scale industrial applications, where more complex environmental factors are involved, data volumes increase, and environmental conditions become more difficult to control. Furthermore, these applications require significant computational and financial resources, which may hinder their application in areas with limited capabilities.

5.2 Future Prospects

A- Developing Smart Monitoring Systems Based on Algae as Bioindicators: Algae are sensitive bioindicators of water quality changes. Smart monitoring systems can be developed using artificial intelligence to analyze algal growth data and physiological and biochemical changes in real time, allowing for early detection of contamination and immediate corrective action.

Integrating Remote Sensing and Artificial Intelligence Technologies to Assess Bioremediation Efficiency: The combination of satellite data, remote sensing technologies, and artificial intelligence models opens a new horizon for monitoring and controlling bioremediation environments over large geographic scales. These integrations enable accurate and effective assessment of pollution sites and algal interactions, enhancing the sustainability and efficiency of environmental restoration operations.

Enhancing the Sustainability of Environmental Remediation Using Adaptive Artificial Intelligence (Adaptive AI): Adaptive AI technologies that rely on continuous learning and adaptation to dynamic environmental variables hold promise for improving bioremediation systems. These systems enable real-time adjustment of treatment strategies based on environmental changes, increasing resource efficiency and reducing environmental side effects.

While AI applications in environmental algal analysis face significant challenges in data, interdisciplinary integration, and industrial expansion, new technical and conceptual developments are opening up bright future prospects. Collaborative work between researchers and engineers, the development of intelligent interactive systems, and the integration of modern sensor technologies will accelerate the transition to more sustainable and effective environmental remediation.

Conclusion:

1- Algae, whether microscopic or multicellular, are among the most important components of aquatic ecosystems, contributing to oxygen production, nutrient cycling, and providing food for many organisms. They possess unique characteristics, such as rapid growth, adaptability, and physiological and biochemical mechanisms that enable them to absorb, accumulate, and decompose environmental pollutants.

2- Algal mechanisms for pollutant removal rely on biosorption, a passive interaction between mineral cell walls and metal ions, biodegradation, where enzymes decompose complex organic compounds into simpler, less toxic substances, and internal accumulation and biotransformation of pollutants.

3- Artificial intelligence techniques, particularly machine learning and artificial neural networks, have revolutionized the analysis of algal bioperformance in pollutant removal. Accurate predictive models can be developed that process vast amounts of experimental data, clarify the factors affecting algal efficiency, and help predict their future behavior in changing environments.

4- Different types of algae are engaged in undertaking different functions in environmental remediation. Green algae (*Scenedesmus and Chlorella*) have been recognized with their great capacity for the absorption of heavy metals and organic matter decomposition. Brown algae (*Sargassum*) contain large amounts of absorbent alginates, while blue-green algae (Spirulina) are nitrogen-fixing and they control organic pollutants and metals.

5- Pollutants that are removable by algae are heavy metals such as lead, mercury, cadmium, and zinc. Several studies have demonstrated their high efficiency for metal removal. They also include organic matter such as petroleum hydrocarbons and pesticides and microplastics with mechanisms like bioaccumulation and biofluorescence.

6- Artificial intelligence techniques enable the treatment of multidimensional data, including physical and chemical water characteristics, levels of contaminants, and composition of algae cells. This accelerates identification of factors influencing impact, classification of effective species, and building accurate prediction models in planning and conducting bioremediation processes.

7- AI implementation in the industry is hindered by the availability of high-quality and complete data, the need for multidisciplinary convergence among environmental scientists and AI designers, and the fact that models cannot be implemented at an industrial scale due to the environmental complexity as well as high computation and costs

8- Promising future prospects include developing smart monitoring systems based on algae as bioindicators for early pollution detection, integrating remote sensing and AI technologies to monitor and analyze biological environments on a large scale, and enhancing sustainability through interactive AI systems that adapt to environmental changes in real time.

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