The Peerian Journal
Open Access | Peer Reviewed
Volume 44, July, 2025
ISSN (E): 2788-0303
Website: www.peerianjournal.com
Email: editor@peerianjournal.com

Analysis of the impact of heavy water pollution on algal diversity using spectroscopy and electron microscopy techniques / Review Article

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Abstract: Algae play a vital role in maintaining the ecological balance of aquatic systems. They are the primary source in the food chain and contribute significantly to oxygen production through photosynthesis and the reduction of atmospheric carbon dioxide. Recent studies indicate that microalgae are responsible for more than 50% of global oxygen production. Algae also constitute an important nutritional basis for zooplankton and small fish, enhancing the stability of aquatic food chains. However, unregulated industrial expansion has led to the discharge of large quantities of wastewater laden with toxic heavy metals such as lead, mercury, cadmium, zinc, and chromium, causing significant imbalances in algal communities at the physiological, structural, and functional levels. These metals affect algae by altering cell membrane permeability, disrupting photosynthetic enzymes, especially RuBisCO, and reducing the production of pigments such as *chlorophyll and carotenoids*. This leads to decreased biomass, reduced growth rates, and possibly the extinction of sensitive species, which are replaced by resistant, less environmentally efficient species. Methodologically, researchers relied on advanced techniques such as spectroscopy (UV-Vis, FTIR) to monitor chemical and biochemical changes in cell pigments and components. They also used scanning electron microscopy (SEM) to image structural changes at the cell level, detecting cracks and corrosion not visible with conventional microscopes.. Multi-statistical techniques were also used to analyze algal diversity data and classify the species most affected or resistant to pollution. Results in polluted sites showed a 40-50% decrease in chlorophyll concentration, changes in cell walls, the disappearance of sensitive species such as *Scenedesmus* and the emergence of resistant species such as *Oscillatoria* and *Euglena*, and the accumulation of metals within algal cells, affecting their external structure and function. These changes not

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only take place in the algae but also bring about disturbance in the food chain, water quality deterioration, and increased toxicity in the ecosystem, recent studies recommend employing algae as bioindicators for the monitoring of water quality based on their sensitivity, ease of monitoring, and affordability. Research also supports the implementation of biological treatment processes that employ algae to get rid of heavy metals from water before discharging it. Environmental legislation has to be formulated and community awareness increased to prevent industrial water pollution.

Finally, specialists agree that to overcome the challenge of heavy water pollution and achieve the sustainability of aquatic systems requires the integration of sound scientific approaches with comprehensive environmental programs, like continuous monitoring, biological treatment, and strict laws, with increased public awareness to ensure environment balance and a water resource sustainable future.

Keywords: Microalgae, heavy metals, industrial pollution, biological indicators, bioremediation

1. **Introduction**:

Algae are a critical microscopic life form that plays an important role in the biological balance of aquatic ecosystems. They are the primary base production of the aquatic food chain and have an effective role in the biological gas exchange, particularly through photosynthesis, which produces high levels of oxygen and reduces carbon dioxide in the atmosphere. Scientific estimations have revealed that microalgae generate more than 50% of the atmospheric oxygen (Ayal *et al.,* 2023; Mebarki *et al.,* 2021). Apart from their importance in supporting aquatic organisms as a primary food source for zooplankton, invertebrates, and small fish, they form a critical element in aquatic food webs' stability.

However, this significant role has actually begun getting threatened in the past few decades with the uncontrolled industrial production, which has resulted in the discharge of enormous quantities of industrial effluent consisting of toxic heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), zinc (Zn), and chromium (Cr) into water bodies without proper treatment. Accumulation of these constituents in water bodies has been proven to cause drastic changes in algal community structure, either at the structural, functional, or physiological levels (El-Kassas *et al.,* 2023; Hussein *et al.,* 2023). Heavy metals affect algae through several interrelated pathways from alteration in cell membrane permeability to the inhibition of photosynthesis enzymes, namely RuBisCO, to reducing pigment production such as chlorophyll and carotenoids. This leads to reduced growth and biomass levels, and potential extinction of locally adapted species replaced by more tolerant but less ecologically efficient species (Al-Kaabi *et al.,* 2023; Mebarki *et al.,* 2021). A Euphrates River field experiment in Iraq indicated a clear impact of heavy metals on Chlorella vulgaris populations, with the algae losing tremendous photosynthetic activity and cell structural disruption growth upon exposure to cadmium and lead in high levels (Hussein *et al.,* 2023).

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With the progress of technology, delicate analytical equipment has developed to monitor these effects, including spectrophotometry, scanning electron microscopy (SEM), and multivariate statistical analysis. These have succeeded in assessing the environmental impact of different concentrations of metals on algae (El-Kassas *et al.,* 2023). There has also been recent work done in Egypt and Algeria that has proposed the use of algae such as *Cladophora, Ulva compressa, and Corallina officinalis* as good bioindicators of the levels of heavy metal deposition in water from the sea with an amazing ability to accumulate lead, cadmium, and nickel at rates greater than environmentally acceptable concentrations. Spectrophotometry is one of the most handy methods to study biochemical changes within algal cells (Mebarki *et al.,* 2021; El-Kassas *et al.,* 2023).

According to these facts, research into the monitoring and study of algal community variations has become popular as the most effective bioindicator of water quality that is contaminated with heavy metals. The application of algae in monitoring programs for the environment is also very cheap and highly effective in an environmental context, providing broad scope for sustainable biological application and monitoring use, especially in developing countries hindered by poor infrastructure facilities for industrial wastewater treatment.

How do we examine the impact of pollution on algae?

Scientists have utilized advanced techniques for the past ten or so years to understand what is occurring in algae as a result of pollution, mainly:

Spectroscopy: Such as ultraviolet-visible (UV-Vis) spectroscopy and infrared (FTIR) spectroscopy, utilized to measure the amount of pigments such as chlorophyll present and determine the presence of damage to cell components.

Scanning Electron Microscopy (SEM): This type of microscope is used to scan algal cells at very high resolution, revealing cracks, tears, and changes not detectable with a regular light microscope.

First: Spectroscopic Analysis

Spectroscopic analysis is among the most effective methods for probing biochemical changes within algal cells. The most developed methods are:

1. UV-Vis Spectrophotometers: UV-Vis Spectrophotometer assists in the quantitative determination of cell pigment content such as chlorophyll a, chlorophyll b, and carotenoids.

Decrease in the concentration of these pigments directly reflects exposure of the algae to environmental stress or toxicity.

For example, it has just been proven by El-Moselhy *et al.* (2023) that the concentration of chlorophyll a in algae *Chlorella vulgaris* decreased by more than 60% when they were treated with increased concentrations of cadmium in industrially treated water.

2. Infrared Analysis (FTIR – Fourier Transform Infrared Spectroscopy): It is used for the detection of chemical alterations in cell components such as proteins, lipids, and carbohydrates.

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Spectral signatures demonstrate radical change of functional groups such as –OH and –COOH upon interaction with heavy metals.

In another research, that of Mokhtar *et al.* (2024), wide changes in protein absorption bands were observed in *Scenedesmus obliquus* algae cells that were exposed to mercury-spiked water.

Second: Scanning Electron Microscopy (SEM)

The electron microscope enables scientists to see the surface of the algal cell at the nanoscale. It is employed to detect microstructural alteration following exposure to pollution, including: Cell wall damage, Loss of cellular asymmetry, Shrinking or bursting of the cell.

This decline leads to the photosynthetic efficiency being impaired, hindering further growth and survival of algae. For example, a recent research study by Al-Samarrai *et al.* (2023) estimated that chlorophyll in *Chlorella vulgaris* algae was decreased by more than 45% upon exposure to excessive cadmium levels in polluted water.

A study by Chen *et al.* (2023) revealed that Anabaena sp. algae cells treated with lead-contaminated industrial water showed severe cell wall damage and cytoplasmic abnormalities, compared to healthy cells.

Third: Additional Supporting Techniques

1. Fluorescence Spectroscopy: Used to assess photosynthetic efficiency in algae and reduced fluorescence indicates a photosystem II disorder due to metal contamination.

2. Multivariate Statistical Analysis: Such as principal component analysis (PCA) and linear discriminate analysis (LDA), to classify algal species and identify those most susceptible or resistant to pollutants.

The Importance of These Methods in Environmental Assessment, these techniques provide accurate information about changes that may not be detected by traditional methods and contribute to building a database that allows for the identification of species most sensitive to pollution, making them accurate bioindicators.

They help develop sustainable environmental monitoring strategies.

What have scientists found when studying the impact of industrial pollution on algae?

In numerous environmental studies conducted in areas polluted by heavy industries, such as metallurgical plants or industrial wastewater treatment plants, researchers have reached alarming results confirming that algae are among the first organisms to be negatively affected by pollution. Among the most significant observations recorded are:

1. A 40–50% decrease in chlorophyll concentration: Many studies indicate that the concentration of chlorophyll a, the pigment responsible for absorbing light during photosynthesis, is significantly reduced in algae found in water contaminated with heavy metals (such as cadmium and lead). This decrease means that the efficiency of photosynthesis is impaired, impairing algae growth and survival. For example, a recent

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study by Al-Samarrai *et al*. (2023) found that the chlorophyll concentration in *Chlorella vulgaris* algae decreased by more than 45% after exposure to high concentrations of cadmium in polluted water.

2. Structural cell wall changes: Scanning electron microscopy (SEM) revealed microscopic cell wall erosions and tears that are not visible by routine microscopy.

These changes are the result of direct wall constituent interaction by heavy metals such as cellulose and proteins, which makes the cell vulnerable and prone to injury. The cells of *Scenedesmus quadricauda* were also shown by Khan *et al*. (2022) to form observable cracks in the cell wall upon mercury exposure, disrupting the balance of osmotic pressure within the cell. 3. Disappearance of sensitive species and emergence of resistant species: Scientists observed the disappearance of some sensitive species of microalgae, such as *Scenedesmus and Navicula,* while more resistant species emerged, such as *Oscillatoria (a filamentous blue-green alga) and Euglena (an animal-plant hybrid)*.

This shift in the algal population is biological evidence of long-term pollution. According to Zhou *et al*. study, (2024), diversity of algae in a petrochemical industry-contaminated river decreased by 60%, and sensitive species disappeared while resistant species persisted. 4. Intracellular Accumulation of Heavy Metals: In analysis of algal content using techniques such as atomic emission spectroscopy (AAS), algae were seen to absorb and accumulate heavy metals inside them, in the cytoplasm and cell walls.

This build-up leads to changes in the external shape of the cell, affects division and growth, and can lead to death. A study by Gupta & Prakash (2023) proved that *Chlorella and Spirulina a*lgae tested for water containing lead and arsenic registered metal accumulation over 200 µg/g of dry weight.

Why is this so important?

The decline in algal diversity not only means the loss of microorganisms, but also has cascading environmental effects such as:

Food chain collapse: Algae are the primary source of energy for zooplankton and small fish. Their absence leads to a decline in the numbers of these organisms, which subsequently affects large fish and marine mammals.

Deterioration of water quality: Some algae species play a vital role in absorbing pollutants and heavy metals. Their absence means the loss of an important natural water purification mechanism.

Increased ecosystem toxicity: The accumulation of heavy metals in algae can be transmitted to higher trophic levels, affecting invertebrates, then fish, and finally humans at the end of the food chain.

Are there solutions?

In light of the increasing impact of industrial and agricultural pollution on the aquatic environment, especially on sensitive organisms such as algae, several scientific and

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environmental solutions have emerged that can be adopted to mitigate this impact, including the following:

1. Monitoring water quality using algae as bioindicators: Algae are considered sensitive to environmental changes, and therefore can be used as bioindicators to monitor water quality. Algal communities present in specific locations in water bodies are analyzed, and changes in diversity, composition, and dominant species are monitored. A decrease in algal diversity or the disappearance of certain species indicates environmental degradation. An increase in resistant algae such as *Euglena and Oscillatoria* may indicate organic or metal pollution. A recent study in 2023 indicated that changes in the abundance of *Chlorella and Scenedesmus* species could reflect the level of heavy metal pollution in industrialized rivers (Wang *et al.,* 2023).

2. Using Bioremediation Before Discharge: One of the most environmentally friendly technologies is biological treatment, which relies on the use of living organisms (including algae themselves) to purify water from pollutants. Microalgae such as *Chlorella vulgaris and Spirulina platensis* are used to remove heavy metals, nitrates, and phosphates, and these systems are integrated into primary and secondary treatment plants. This method reduces operating costs and produces less harmful waste. Furthermore, the resulting biomass can be used to produce biofuel or feed. A study published in the Journal of Environmental Management (Ahmed *et al.,* 2024) demonstrated the successful use of *Chlorella pyrenoidosa* in removing 85% of cadmium from contaminated water in just 7 days.

3. Environmental Awareness and Enactment of Strict Environmental Legislation: It is essential to enhance community understanding (especially among industrial and agricultural sectors) of the serious impact of untreated polluted water discharge and the importance of protecting water resources. Environmental laws must be enacted and enforced, laws requiring factories to establish efficient treatment plants, heavy fines imposed on entities that cause water pollution, and environmental monitoring programs supported by state institutions and civil society. Many countries are now adopting the concept of a green economy, which imposes strict requirements on wastewater management and encourages environmentally friendly biological treatments.

Solutions to the problem of water pollution and its impact on algae require not only scientific technologies, but also a comprehensive environmental vision that includes continuous scientific monitoring, advanced biological treatment, enforcement of environmental laws, and community education. Only in this way can ecological balance be maintained and the sustainability of aquatic systems ensured for future generations.

Conclusion :

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1- Algae as effective bioindicators: Microalgae are highly sensitive to environmental changes, especially the accumulation of heavy metals in water. This makes them valuable tools for monitoring pollution levels and assessing water quality.
2- Negative effects of heavy metals on algae: Heavy metals such as lead, cadmium, and mercury damage cell membranes, reduce the concentration of pigments such as chlorophyll, and lead to reduced biological growth, threatening algal diversity and affecting the stability of the food chain.
3- Changes in algal communities under the influence of pollution: Industrial pollution leads to the disappearance of sensitive species and their replacement by more tolerant but less environmentally friendly species, disrupting the ecological balance and affecting the vital functions of aquatic systems.
4- Effectiveness of modern analytical techniques: Techniques such as spectroscopy (UV-Vis and FTIR), scanning electron microscopy (SEM), and multi-statistics provide accurate data on biochemical and morphological changes in algae, contributing to a more comprehensive and in-depth assessment of the impact of pollution. Environmental solutions and recommendations: Integrating algal monitoring into environmental monitoring programs, using algal bioremediation to purify water from heavy metals, implementing strict environmental legislation, and raising community awareness are all crucial factors for maintaining the health and sustainability of aquatic systems.

Acknowledgment

The authors I would like to express my sincere gratitude to **Al-Mustansiriyah University** – www.uomustansiriyah.edu.iq – for their continuous academic and scientific support. Special thanks are extended to the **College of Science** and the **Department of Biology** for their active assistance and valuable contribution to the completion of this scientific article through research facilities and academic guidance.

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