The Influence of Low-Level Radioactivity on Benthic Diatom Communities

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Abstract:

Low-level ionising radiation is a persistent environmental factor in many freshwater ecosystems, particularly in mineral springs and areas affected by historical uranium mining. However, its ecological effects under natural field conditions remain poorly quantified. This study investigates the influence of naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TE-NORM) on benthic diatom communities using field observations from mineral springs and a former uranium mining wetland in Southern Iraq. Diatom assemblages were analysed using morphological and genetic approaches and related to environmental and radiological parameters. Results indicate that radioactivity contributes to the structuring of diatom communities by influencing species dominance and composition, while overall species richness is primarily controlled by physico-chemical conditions. Low-level radioactivity therefore acts as a chronic ecological constraint rather than an acute stressor.

Keywords: Low-Level Radioactivity, Diatoms, Mineral Springs, Wetlands, Aquatic Ecology.

1. Introduction:

Background radioactivity of a natural origin has prevailed since the formation of Earth, serving as a constant source of ionizing radiation affecting life (Martell, 1992; Garzón & Garzón, 2001). Natural radionuclides, such as uranium-238, thorium-232, and potassium-40, are common throughout geological materials and add a chronic exposure at low doses (Henner, 2002). Consequently, these ecosystems have evolved in the presence of long-term exposure to ionizing radiation to a varying extent thereon loci depending on the geology and hydrology.

While the biological effects of high-dose radiation are well documented, particularly in medical and industrial contexts, the ecological effects of chronic low-level exposure remain uncertain (Morgan & Bair, 2013). Most ecological studies addressing radiation effects have focused on accidental releases or experimental exposure, which may not reflect realistic environmental conditions (Møller & Mousseau, 2013). On the contrary, environments characterized by naturally high radiation provide extremely unique opportunities to study long-term exposure under constant conditions.

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Consequently, freshwater ecosystems are best-suited for such research; mainly since radionuclides in chemical dissolution can be carried way with the current of ground or surface water, thereby subjecting entire biological communities for longer age (Brechignac et al., 2016). However, special attention needs to be paid to benthic organisms as sediment deposition may accumulate radionuclides, thus possibly creating long-lasting sources of exposure in some cases (Bradshaw et al., 2014).

Diatoms are unicellular photosynthetic algae that dominate benthic biofilms in many freshwater systems. Their high diversity, rapid life cycles, and sensitivity to environmental change make them widely used indicators of ecological conditions (Mann & Vanormelingen, 2013; Smol & Stoermer, 2010). In addition, the siliceous frustules of diatoms are well preserved in sediments, allowing reconstruction of past environmental conditions. The objective of this study is to assess how low-level natural and anthropogenic radioactivity influences benthic diatom communities under field conditions.

2. Description of Study Environments

2.1 Mineral Springs

The issues pertaining to the mineral springs are 100% connected to the geological setting and that is what makes the groundwater so unique for these aquatic ecosystems. The property of such water is mostly dependent on the stability of the geological formations around it. Well, with the radiation coming from high levels of uranium and radon in some places, it is not wrong to speak of the source as having naturally enhanced radioactivity.

On the one hand, the springs can be seen as habitats that differ from others in both surroundings and stability and this is why they are ecological islands. These habitats may condone the existence of very rare species.

2.2 Wetlands Associated with Former Uranium Mines

Wetlands, which are close to the old uranium mining places, might gather radionuclides in the ground. This area makes a place for the nature to live and among the remains of biological entities trapped in the mud, the diatoms' walls are the most common.

Table 1. Comparison of Studied Environment Types

Environment	Hydrology	Main Exposure Pathway
Mineral springs	Groundwater	Dissolved radionuclides
Wetlands	Surface and groundwater	Sediment-bound radionuclides

3. Materials and Methods

3.1 Sampling Design

Benthic diatoms, from multiple substrates such as stones, sediments, and aquatic vegetation, were sampled in the mineral springs. The whole process was planned meticulously to control the variability arising from the differences in the microhabitat.

In a swampy zone, cores were dug out of the sediment, and then they were cut into sections at regular depth intervals. Every piece of sediment was a different time period, so that the scientists could infer historical diatom communities.

3.2 Laboratory Preparation

To clean samples and to separate diatom shells from the organic matter present in the samples, chemicals were used in the procedure, and in the end, the cleaned shell material was glued to microscope slides to be archived.

3.3 Identification and Data Processing

Identification of diatoms has mainly relied on light microscopy and through comparison with relevant standard taxonomic references. In rare and specific cases, identification using morphological characters has relied on DNA-based methods such as metabarcode analysis.

3.4 Environmental Measurements

Exposure conditions were characterised based on the measurement of physicochemical parameters and radionuclide

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concentrations.

Table 2. Environmental Parameters Measured During Sampling

Parameter	Relevance
pH	Controls species tolerance
Conductivity	Reflects mineralisation
Uranium concentration	Indicator of radioactivity
Radon activity	Indicator of gaseous exposure

4. Results

4.1 Physico-Chemical and Radiological Gradients

Environmental conditions varied strongly among the studied mineral springs. Conductivity values ranged from weakly mineralised waters to highly mineralised systems, reflecting differences in geological substrates and groundwater residence times. Water temperature remained relatively stable within individual springs but differed between sites.

Silver-110 levels presented considerable heterogeneity between different locations and showed no systematic correlation with Tan, while the activity of radium-222 also showed variability that did not correlate with the concentration of uranium. This suggests that the two decaying elements are being mobilized by differing geochemical barriers. Such differences equate to variable long-term exposure conditions across sites.

Table 3. Summary of Physico-Chemical and Radiological Gradients Across Mineral Springs

Variable	Low	Medium	High
Conductivity	<500 μS/cm	500–3000 μS/cm	>3000 μS/cm
Uranium-238	Background	Elevated	High
Radon-222	Low	Moderate	High

4.2 Diatom Species Richness Patterns

Diatom species richness varied markedly among sites. Among the springs of moderate to high conductivity and stable chemical conditions, the highest numbers of taxa were supported. Contrarily, springs with extreme mineralisation or radionuclide levels exhibited an evident decrease in richness.

Species richness tended to gradually decrease with increased uranium and radon levels along the gradient of radionuclide concentration. Although the taxa would not abruptly disappear, the most radioactive springs maintained quite diverse diatom assemblages. This slow escalated loss of the number of species clearly points towards a process of ecological filtration rather than one of infernal toxicity.

Table 4. Mean Diatom Species Richness Across Radioactivity Classes

Radioactivity Class	Mean Richness	Variability
Low	High	Moderate
Medium	Moderate	Moderate
High	Lower	Low

4.3 Community Composition and Dominance Structure

Community composition varied strongly by environmental value. Low-radioactivity springs were characterized by relatively uniform assemblages, with a great number of taxa contributing similar quantities to the total abundances. In contrast, a higher degree of dominance was encountered by a limited number of species in highly radioactive springs.

The population of Planothidium frequentissimum showed dominance in contexts of significantly higher levels of uranium-238 and radon-222. In the low-radioactivity context, other taxa, such as species of Achnanthidium, were more common but declined in relative abundance with increasing levels of radioactivity.

Table 5. Relative Abundance of Dominant Taxa Across Radioactivity Levels

Taxon	Low	Medium	High
Planothidium frequentissimum	Low	Moderate	High
Achnanthidium spp.	High	Moderate	Low
Mixed taxa	High	Moderate	Low

4.4 Morphological and Genetic Diversity

Metabarcoding of DNA and morphological differentiation exposed altered community dynamics in comparable patterns. Genetic data confirmed the reduction of within-species variability in dominant taxa at sites with high radioactivity. Even with smaller decreases in genetic diversity, variability is clearly established throughout all localities. This implies that chronic exposure modifies the genetic structure without eliminating any variation.

4.5 Temporal Patterns in Fossil Diatom Assemblages

Fossil diatom assemblages from the mining-associated wetland showed gradual temporal changes. Assemblage composition remained broadly similar before, during, and after uranium mining activities. No abrupt community shifts were observed in relation to periods of maximum uranium extraction.

Table 6. Summary of Fossil Diatom Assemblage Characteristics Through Time

Period	Community Structure	Degree Of Change
Pre-mining	Diverse	Stable
Mining	Similar	Minor shifts
Post-mining	Similar	Stable

4.6 Diatom Species Richness

Site biodiversity was such a varied parameter. Those springs having moderate conductivity and stable chemistry proved the most species-rich in all. Springs of extreme conditions cannot support such richness of species. A gradual decline in species richness was noted as one moved up the radioactive gradient from lake water towards uranium and radon concentrations, but no complete loss of species was observed.

Table 7. Mean Diatom Species Richness Across Radioactivity Classes

Radioactivity level	Mean richness
Low	High
Medium	Moderate
High	Lower

4.7 Community Composition and Dominance

Community composition across springs differed unexpectedly significantly. Whereas lower Anglican fauna occurred in lesser radioactivity springs, higher radioactivity springs had more or less limited taxa. Considering the radon and uranium levels, Planothidium frequentissimum was one of the common taxa occurring in the spring.

Table 8. Dominant taxa observed across radioactivity levels

Radioactivity Level	Dominant Taxa
Low	Mixed assemblages
High	*Planothidium frequentissimum*

4.8 Genetic and Fossil Evidence

Genetic analyses revealed a decrease in intrapopulation variability in some widespread taxa at highly radioactive sites, indicating population-level selection at work. A fossil diatom assemblage from the mining wetland exhibits gradual, long-term, temporal changes and not directionally linked to mining periods, hence indicating community-structural stability over time (Baker, 2023).

5. Discussion

Major physico-chemical factors that influence species richness include conductivity and ionic composition. The elevation increased with radioactive secondary effects-both in the condition of high species richness. Community composition was sensitive enough that the dominance could shift even where species richness was pretty high. The difference brought forward questions about looking at the community structure rather than abundance when assessing the ecological consequences of prolonged stress.

Planothidium frequentissimum is emerging as the chronically exposed organism in the case of high-radiative hot springs. There should certainly be some form of indicative value of this taxon with regard to radioactivity from some sites that lead on to connecting increase in the radon or uranium levels. However, indirect effects that might have occurred from water

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chemistry and competitive interactions could not be entirely ruled out.

On the other hand, the present phenomenon of low genetic diversity at large taxa from extremely radioactive areas could suggest that some form of selection is operating at the population level. This trend might be interlinked with kind of environmental sieving and local adaptation. Meanwhile, in each site, at least a bit of genetic diversity remains, despite the applications of chronic exposures, presumably lessening a greater degree of genetic bottlenecks.

Siliceous diatom flora is proven to be a rich archive in properties for interpretation of long-term matters. A lack of obvious assemblage shifts might attest to community stability during the period of available uranium mining. However, the more significant shifts in dominance, and composition might display a sustained impact to the environment, while invisible during particularly short-term regimes.

6. Conclusion

Hence, fieldwork at hand might help in understanding the very low natural and anthropogenic radioactivity influence on benthic diatom communities in the freshwater ecosystem. Diatom assemblages persisted under a huge environmental and radioactive gradient, implying that sustained exposure to low-radiation doses does not result in immediate ecological collapse.

Results show that radioactivity yields a predominant effect on the assemblage composition and species dominance rather than the species richness. The final results revealed that major types of diatom diversity have been controlled by physicochemical parameters including ionic composition and conductivity, with radioactivity remaining a perpetually enforced secondary constraint. So, in the current study, the radiation has been considered a long-lasting ecological filter. The suggestion arises that examining the structure of the community, rather than just richness-related parameters, produces much more informatics from a standpoint of ecological stress.

Comparison of fossil diatom assemblages in mining-damaged wetlands is essential for our understanding of how operational impacts of ancient uranium extraction have affected an ecosystem. The lack of sudden severe shifts in community composition suggests a partial degree of resilience of the diatom communities to old mining activities, while tweaks or knobs might have slowly led to alterations. Long-term cumulative impacts of mining were, however, probably present and should not be ignored.

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