



## Phytoremediation of mining wastewater using *Nelumbo nucifera* Gaertn and *Nelumbo nucifera* Lutea (Nymphaeaceae) species

Valdina Aïssi J.<sup>1</sup>, Soro Y.<sup>1\*</sup>, Mama D.<sup>2</sup>, Adandédji F.<sup>2</sup>

<sup>1</sup>Laboratoire des Procédés Industriels de Synthèse, de l'Environnement et des Energies Nouvelles (LAPISEN), Institut National Polytechnique Félix HOUPHOUËT-BOIGNY de Yamoussoukro, BP 1093 Yamoussoukro, Côte d'Ivoire

<sup>2</sup>Institut National de l'Eau du Bénin, Abomey-Calavi, Bénin

\*Corresponding author: E-mail: [yaya.soro@inphb.ci](mailto:yaya.soro@inphb.ci)

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### Abstract

Mining activity has significant impacts on the quality of ecosystems, particularly aquatic ones. It is a source of water pollution by heavy metals and other toxic contaminants. Phytoremediation was used as a method for treating mining wastewater in locality of Kokumbo in Côte d'Ivoire using hyper-accumulating plants, including *Nelumbo nucifera* Gaertn and *Nelumbo nucifera* Lutea. The study found that plants alkalized the medium from an initial pH of 6.2 to pH values between 8.1 and 8.5. The study shows an increase in water temperature from 25.2 to 30.1-32.1, a decrease in water electrical conductivity from 1152  $\mu\text{s}/\text{cm}$  to 200-270  $\mu\text{s}/\text{cm}$ , representing reduction rates of 82.60 to 87.11%, and an improvement in water turbidity from 1820 NTU to 302-505 NTU, representing reduction rates of 72.25 to 83.41%. The experimental device significantly reduced Iron and Nickel levels, with reduction rates ranging from 88.88 and 94.38% for Iron and from 69.23 and 84.62% for Nickel. For all the parameters tested, combination of the two plants gave the best results. This study confirms phytoremediation as an ecological and economic alternative for managing mining pollution in Kokumbo.

## 1. Introduction

Water accounts for 70% of the Earth's crust and is increasingly degraded or polluted due to certain anthropogenic activities such as industrial, agricultural and domestic activities (Aïcha and Kaouthar, 2021; Ali et al., 2021). Mining operations use enormous quantities of water at all stages of ore processing (Cissé, 2019) which they release into the environment without treatment. They are major contributors to pollution of aquatic ecosystems due to the discharge of effluents rich in heavy metals and toxic substances (Alassane Boukari et al., 2022; Ben Ghnaya et al., 2013; Akoto et al., 2017). Their tendency to accumulate in living organisms and to concentrate along food chains is responsible for many diseases (Alizadeh-Kouskuie et al., 2020; Mununga Katebe et al., 2023, Gazi Hasan et al., 2025).

To remove these pollutants from water, several techniques including membrane filtration (Nadeem et al., 2019), advanced oxidation processes (Ghughe and Saroha, 2018; Latifi et al., 2025), electrocoagulation (Ano et al., 2019), adsorption on porous materials (Gouré bi et al., 2021; Errich et al., 2021; Sako et al., 2025) and phytoremediation (Ali et al., 2013) have been used. The latter is a

phytotechnology that combines a set of techniques using plant species to extract, contain or degrade inorganic or organic pollutants. It can be applied *in situ* on a wide variety of polluted sites (agricultural soils, brownfield sites, excavated sediments) in rural and urban areas (Bert *et al.*, 2012) and it appears to be a promising ecological solution, capable of mitigating the adverse effects of mining pollution on the environment. Thus, several hyperaccumulator plants such as *Typha latifolia* and *Phragmites australis*, *Eichhornia crassipes* and *Vetiveria zizanoides* (Salt *et al.*, 1998), (Ghosh and Singh, 2005) have been used for their ability to absorb heavy metals. Unfortunately, despite the ability of *Nelumbo nucifera* Gaertn and *Nelumbo nucifera* Lutea to accumulate certain metals in their tissues (Ali *et al.*, 2013, Rezanian *et al.*, 2016), they are rarely used in phytoremediation.

The present study aims to evaluate the effectiveness of *Nelumbo nucifera* Gaertn and *Nelumbo nucifera* Lutea in improving some parameters and reducing contamination by certain heavy metals in the mining waters of Kokumbo, a locality in Ivory Coast.

## 2. Materials and Methods

### 2.1. Materials

#### 2.1.1. Study Area

Kokumbo is located between latitudes 6.7667° N and -5.2667° W in the center of Côte d'Ivoire and is characterized by a humid tropical climate. Mining is practiced by both industrial companies and artisanal miners, resulting in significant pollution of water resources. It is located 250 km from Abidjan, the economic capital, and 40 km from Yamoussoukro, the political capital.

Kokumbo locality is subject to a subequatorial climate influenced by the seasonal alternation between dry trade winds of Harmattan and humid winds of Guinean monsoon (Soro *et al.*, 2015). This dynamic generates a bimodal climate regime typical of degraded transitional forest areas, with major implications for water availability, soil erosion and plant growth as part of phytoremediation. The average annual rainfall varies between 1,200 and 1,500 mm. The regime is bimodal, with two rainy seasons: a long season (April-July) and a short season (September-October), separated by a short drought in August. The long dry season extends from November to March, with minimums around 25 mm in January (Koné *et al.*, 2018). This distribution strongly influences soil leaching, heavy metal mobility, and optimal timing of plant remediation species, which need a long and humid growing season to be effective (Ndong *et al.*, 2020). Average temperatures remain relatively stable throughout the year, ranging from 25 to 28 °C. March is generally the hottest month ( $\approx 28$  °C), while July-August is the coolest period ( $\approx 25$  °C), due to high cloud cover and increased humidity (Kouassi *et al.*, 2014). Relative humidity often reaches 85 to 90% during rainy season, promoting degradation of organic matter and bioavailability of certain soil chemicals (Tóth *et al.*, 2016). This thermal constancy combined with significant precipitation constitutes a favourable context for phytoremediation, particularly for tropical species tolerant to acidic soils and high metal loads.

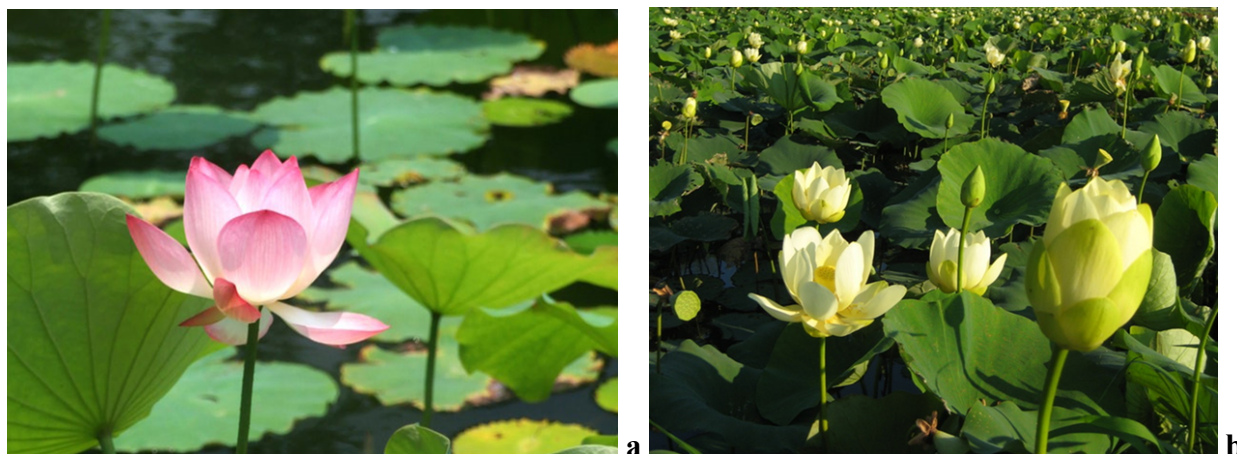
#### 2.2.2. Plant material

Plant material consisted of *Nelumbo nucifera* Gaertn (NG) and *Nelumbo nucifera* Lutea (NL) (Figure 1). Their selection was based primarily on their ability to survive in a polluted environment, their rapid growth, their dense root system, and their ability to accumulate metals in their tissues (Ali *et al.*, 2013).

#### 2.3.3. Different types of substrates

Different types of substrates used consisted of alluvial sand, small crushed gray gravel, and large crushed gray gravel (Figure 2). These substrates were washed and dried (Plate 1) because their physical and chemical properties directly influence the bioavailability of heavy metals and, consequently, the

efficiency of plants in their absorption or stabilization process (Pulford and Watson, 2003 and Ali et al., 2013).



**Figure 1.** Photographs of *Nelumbo nucifera* Gaertn (a) and *Nelumbo nucifera* Lutea (b)



Alluvial sand

Small crushed gravel

Large grey crushed gravel

**Figure 2.** Photographs of different substrates used

## 2.2. Methods

### 2.2.1. Sample Collection

Wastewater samples were collected from Kokoumbo mine site in 25L polyethylene containers under normal flow conditions (not during rain or spill events) and at the surface. The collected samples were transported to laboratory for further analysis.

### 2.2.2. Sample Analysis

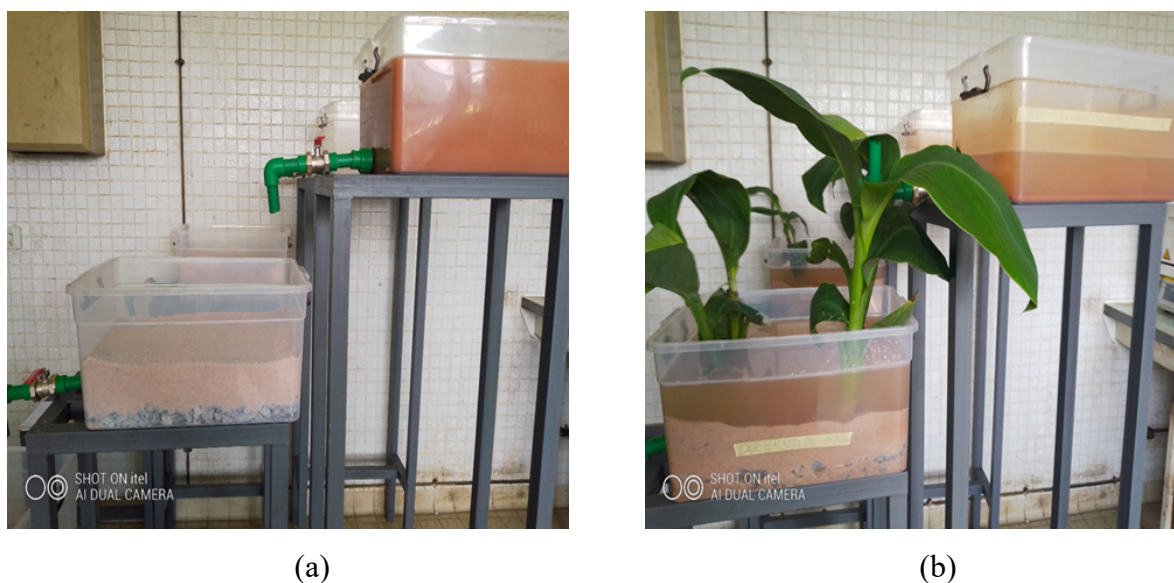
Various physical and chemical parameters were measured before, during, and after 31 days of phytoremediation. These measurements were used to evaluate process performance. Hydrogen potential and temperature were measured using the potentiometric method with a glass electrode according to AFNOR NF T 90-008 standard of February 2001. Conductivity was determined using the conductometric method described by the ISO 7888:2021 standard. Turbidity was measured using the incident light attenuation measurement method described in AFNOR NF EN ISO 7027 standard of March 2000. Heavy metal concentrations (Fe and Ni) were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The effectiveness of phytoremediation was assessed by the removal rate ( $\eta$ ) given in Eqn. 1 in which  $C_{\text{before}}$  and  $C_{\text{after}}$  represent concentrations of the pollutant before and after phytoremediation (USEPA, 2000). A high rate indicates good phytoremediation effectiveness:

$$\eta = \frac{C_{before} - C_{after}}{C_{before}} \times 100 \quad \text{Eqn. 1}$$

### 2.3.3. Implementation of the mining wastewater treatment system

Treatment system consisted of a series of 12.5 m<sup>3</sup> experimental tanks containing a filter layer composed of sand, large and small gravel, and surmounted on iron supports. Collected water underwent pre-treatment or decantation in the first tank, thus removing the coarsest suspended matter (**Figure 3a**) (Nakib *et al.*, 2020). As the raw water consisted of sludge, decantation was carried out for two days according to Stokes' law to maximize deposition of these particles (Degrémont, 2005). After decantation, valves were opened and water was sent to vegetated basins of *Nelumbo nucifera* species alone or in combination for phytoremediation (**Figure 3b**). Thus, water percolated vertically through the filter layer of basins for 31 days.

Young plants of *Nelumbo nucifera* Gaertn and *Lutea* were obtained locally and then acclimatized for two weeks in a healthy substrate (without contamination) away from direct sunlight so that they could properly implant before being exposed to more stressful conditions (Zhou *et al.*, 2011). The plants were then placed in trays filled with clean substrate and irrigated with water containing known concentrations of heavy metals (Iron and Nickel) for 31 days to evaluate plants' reaction to controlled contamination (Marchand *et al.*, 2010). After testing, percentage reduction rate was calculated to measure treatment effectiveness (Yoon *et al.*, 2006).



**Figure 3.** Depollution system consisting of experimental basins

## 2.5. Data Processing

Microsoft Excel was used to calculate average, maximum, and minimum values for each parameter and chemical element, as well as to produce graphs.

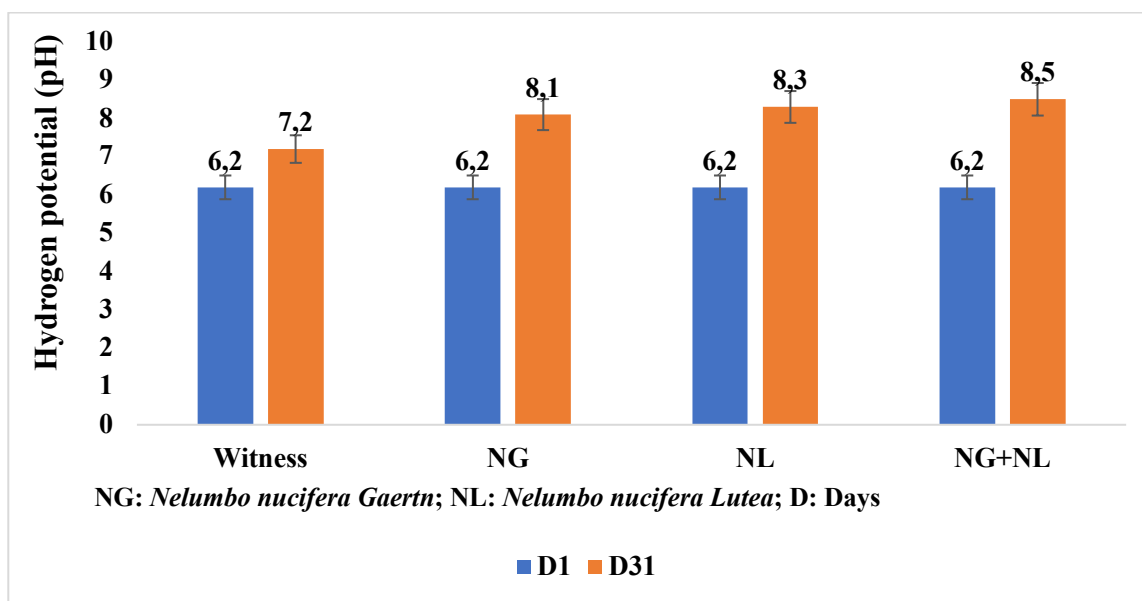
## 3. Results and Discussion

### 3.1. Evolution of physical and chemical parameters

#### 3.1.1. Evolution of Hydrogen Potential

**Figure 4** shows the variation in Hydrogen potential (pH) from day 1 to day 31 of phytoremediation. **Figure 4** shows that pH of water at the end of treatment ( $8.10 \pm 0.06$  to  $8.50 \pm 0.06$ ) is higher than that at the beginning of treatment ( $6.20 \pm 0.05$ ) in all basins, including the control basin. This variation, not correlated with a phytoremediation process, could be linked to abiotic phenomena

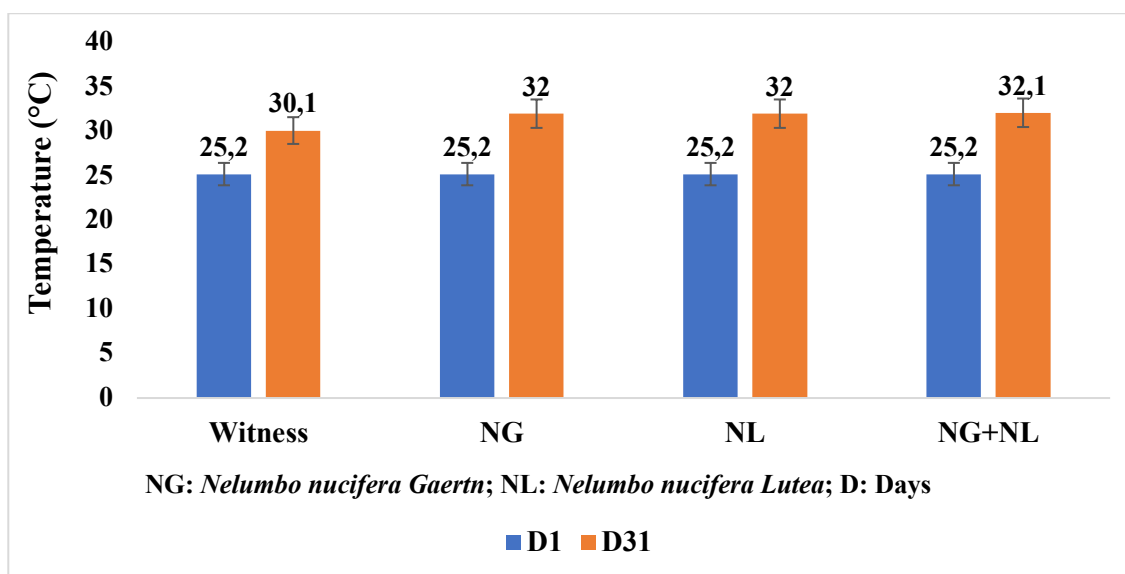
such as evaporation, carbonate precipitation or endogenous microbial activity. In contrast, systems containing *Nelumbo nucifera* species alone or in combination show a clear tendency towards alkalinization of the medium at the end of the treatment with the highest pH value observed for combination of the two plants. This significant increase in pH in vegetated systems agrees with the work carried out by Zhou *et al.* (2007) and could be explained by several biological and biochemical mechanisms linked to *Nelumbo nucifera* rhizosphere. Indeed, during photosynthesis, aquatic plants absorb dissolved carbon dioxide (CO<sub>2</sub>), causing a decrease in carbonic acid concentration and, consequently, an increase in pH. Furthermore, root activity could promote release of hydroxyl ions (OH<sup>-</sup>) and absorption of cations such as Fe<sup>2+</sup> and Ni<sup>2+</sup>, thus contributing to alkalinization of the medium (Zhou *et al.*, 2007). Medium alkalinization could also be linked to the intense metabolic activity of aquatic macrophytes, especially in the active growth phases (Lu *et al.*, 2010). The higher pH value obtained in the combined NG+NL treatment could suggest a functional synergy between the two varieties, probably due to a greater overall biomass and increased photosynthetic activity. Medium alkalinization could promote precipitation of certain heavy metals in insoluble complexes form and could influence speciation of metals present in water. Indeed, in a more basic environment, iron and nickel tend to precipitate as hydroxides, which could enhance decontamination effect, but also reduce their long-term bioavailability for plants. This dynamic highlights the importance of controlling pH in phyto-assisted treatment systems.



**Figure 4.** Evolution of hydrogen potential during phytoremediation

### 3.1.2. Temperature Evolution

**Figure 5** shows temperature evolution from day 1 to day 31 of phytoremediation. **Figure 5** shows that water temperatures at the end of treatment ( $30.100 \pm 0.007$  to  $32.000 \pm 0,005$ ) were higher than that at the beginning of treatment ( $25.200 \pm 0.001$ ) in all basins, including that of the control. This temperature increase could reflect cumulative effects of ambient climate and prolonged exposure to sunlight. Combination of plant species has less influence on medium temperature, unlike pH. Similar results have been reported in literature (Vesk *et al.*, 1999). Temperature increase in vegetated tanks could be attributed to increased biological activity, particularly root respiration and photosynthesis, which release thermal energy into the environment.



**Figure 5.** Temperature Evolution during Phytoremediation

Indeed, aquatic plants can locally modify thermal properties of their environment, notably by modifying absorption of solar radiation and by heating water layer close to roots by rhizospheric microclimate effect (Vesk *et al.*, 1999). In addition, plant biomass density could contribute to local temperature rise, especially in shallow environments (Gopal, 1999). Temperature rise, although moderate (less than 2°C compared to the control), could indirectly contribute to performance of plants in absorption of heavy metals, by stimulating their metabolism. Indeed, many enzymes involved in biosorption or in assimilation of metals are more active at moderate to high temperatures (25–32°C) such as those observed in this study.

### 3.1.2. Evolution of electrical conductivity

Electrical conductivity (EC) is a global indicator of dissolved ions concentration in water, including salts, metals, nutrients, and other ionic species. The EC results measured at the beginning (D1) and at the end (D31) of the experiment are presented in **Table 1**.

**Table 1.** Evolution of the electrical conductivity

Electrical conductivity (µS/cm)	Day 1	Day 31	Abatement rates (%)
Control	1552	1545	0.45
NG	1552	270	<b>82.60</b>
NL	1552	265	<b>82.93</b>
NL+NG	1552	200	<b>87.11</b>

The control without plant species shows a slight decrease in conductivity, from 1552.000±0.001 to 1545.00±0.005 µS/cm, an insignificant reduction of 0.45%, which indicates a quasi-stability of untreated system. In contrast, vegetated basins show a strong reduction in conductivity from 1552.000±0.001 to 270.00±0.007 µS/cm (i.e. 82.60% reduction) for NG, from 1552.000±0.001 to 265.001±0.001 µS/cm (i.e. 82.93% reduction) for NL and from 1552.000±0.001 to 200.000±0.006 µS/cm (i.e. 87.11% reduction) for combination of the two species. This sharp decline demonstrates *Nelumbo nucifera's* ability to extract or immobilize dissolved ions in system, particularly through accumulation in tissues, adsorption on root surfaces, or precipitation in rhizosphere. Combination of the two species (NG+NL) give the best performance, further confirming a synergistic effect between

these two varieties. Results obtained are similar to those of [Verma and Suthar \(2014\)](#) and [Lu et al. \(2010\)](#), who showed that *Nelumbo nucifera* is able to reduce water conductivity through selective absorption of cations ( $K^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ ) and metals (Fe, Ni, Zn), in addition to promoting sedimentation of dissolved solids through root action. Decrease in EC is an indirect indicator of reduction in overall pollutant load, which confirms overall effectiveness of phytoremediation system. In addition, according to [Vymazal \(2011\)](#), conductivity generally decreases in systems containing plants, as they use nutrients and metals present in ionic form, thus helping to purify water. This dynamic is often correlated with developed plant biomass, specific root surface area and residence time of water in the system. NG+NL treatment, by reducing EC to 200  $\mu S/cm$ , reflects a marked demineralization of the medium, reflecting an ion depletion which may also result from precipitation induced by previously observed alkalization of the medium. This link between alkalization, temperature and reduction of EC is typical of mature phytostabilized media and confirms performance of the coupling of the two varieties in regeneration of contaminated water.

### 3.1.2. Turbidity Evolution

Turbidity is an indicator of suspended particulate matter content in water, including fine sediments, colloids, organic matter, and sometimes aggregates containing heavy metals. It is directly related to the visual quality of water and its particulate pollutant load. It is an important parameter from the aesthetic and health perspectives of treated water, as it influences transparency and light penetration, essential conditions for natural self-purification. Turbidity results at the beginning (Day 1) and end of treatment (Day 31) are shown in [Table 2](#).

**Table 2.** Turbidity evolution in water samples collected at Kokumbo

Turbidity (NTU)	Day 1	Day 31	Abatement rates (%)
Control	1820	1792	1.54
NG	1820	505	<b>72.25</b>
NL	1820	403	<b>77.86</b>
NL+NG	1820	302	<b>83.41</b>

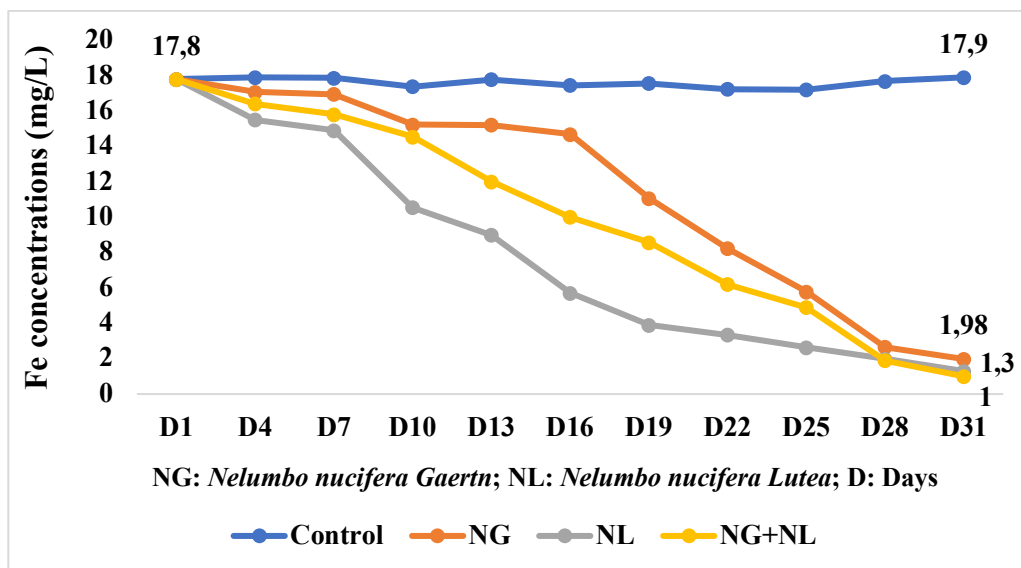
The results show that for the control, turbidity remains practically stable, varying from 1820 to 1792 NTU, i.e. a negligible reduction of 1.54%. This result indicates the absence of a significant natural settling or filtration mechanism in unvegetated medium. Conversely, treatments with *Nelumbo nucifera* show marked reductions in turbidity from 1820 to 505 NTU (72.25% reduction) for NG, from 1820 to 403 NTU (77.86% reduction) for NL and from 1820 to 302 NTU (83.41% reduction) for combination of NG and NL. These results highlight the remarkable ability of *Nelumbo nucifera* to clarify turbid waters. This efficiency would be due to dense root and foliar architecture of *Nelumbo nucifera*, which is capable of acting as a physical barrier to resuspension of sediments, as well as to several combined mechanisms such as stabilization of fine particles in root zone, physical action of roots which slow down water flows and promote sedimentation (rhizospheric filter effect), adsorption of colloids and micro-aggregates on root surfaces or in biofilm matrix and immobilization of precipitated metal particles in alkalized medium ([Gopal, 1999](#)). The best performances were obtained in combined treatment of NG and NL suggesting a synergy between the two varieties in creation of a dense and biologically active micro-environment. These results agree with those of [Alkorta et al. \(2004\)](#) who reported a significant decrease in turbidity in phytosanitary systems, linked to root growth and

stabilizing effect of plants on fine particles. The results obtained show an effective clarification of the medium, favourable to an overall improvement in ecological quality of water.

### 3.2. Evolution of heavy metal concentrations

#### 3.2.1. Evolution of iron concentrations

The evolution of iron (Fe) concentrations during phytoremediation is presented in **Figure 6**. The results obtained show minor, non-significant variations (17.8 to 17.9 mg/L) for control (without plants), confirming the absence of an active natural purification process. In contrast, systems containing *Nelumbo nucifera* species, alone or in combination, reveal a significant decrease in dissolved iron concentrations. After 31 days of treatment, final Fe concentrations reached 1.98 mg/L for NG, 1.3 mg/L for NL and 1.0 mg/L for NG+NL combination, corresponding to abatement rates of 88.88 %, 92.70 %, and 94.38 %, respectively. These results indicate the remarkable iron absorption and/or accumulation capacity of both *Nelumbo nucifera* varieties, with maximum efficiency when combined. These performances could be explained by physiology of *Nelumbo nucifera* which has root and leaf tissues capable of bioaccumulating heavy metals (Zhou *et al.*, 2007). *Nelumbo nucifera* also secretes secondary metabolites, including phenols and flavonoids, capable of chelating metal ions, thus facilitating their assimilation or precipitation (Shanab *et al.*, 2012).



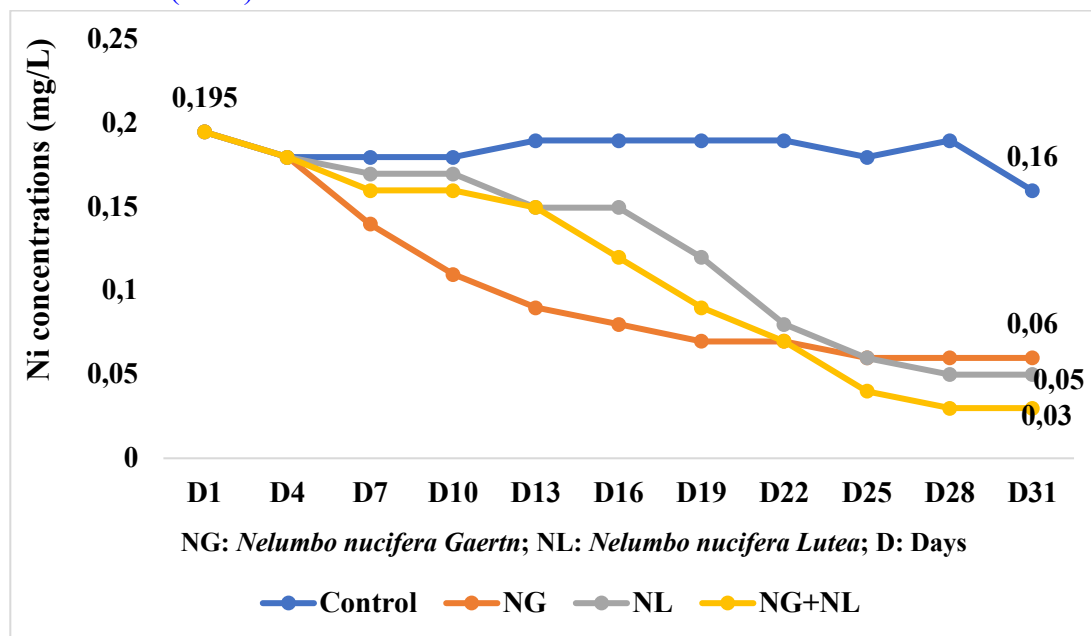
**Figure 6.** Evolution of Fe content during phytoremediation

In addition, presence of microorganisms in rhizosphere could also play a complementary role in iron transformation and immobilization (Lu *et al.*, 2010). The slightly lower efficiency observed with NG compared to NL could suggest the role of genotypic difference in iron absorption capacity. The increased efficiency of NG+NL combination suggests a synergy between the two varieties, probably related to increased functional diversity. These results agree with some previous studies (Shanab *et al.*, 2012; Lu *et al.*, 2010). Thus, the use of *Nelumbo nucifera* species, alone or in combination, is particularly promising for aquatic applications.

#### 3.2.2. Evolution of Nickel Concentrations

Evolution of Nickel (Ni) concentrations during phytoremediation is presented in **Figure 7**. The results obtained show a relative stability of Ni contents, ranging from 0.16 to 0.19 mg/L, with control (without plant), thus confirming the absence of spontaneous decontamination mechanisms in the

system. In contrast, systems containing *Nelumbo nucifera* reveal a high removal of dissolved nickel over time. At day 31, residual concentrations reached 0.06 mg/L for NG (69.23% abatement), 0.05 mg/L for NL (74.36% abatement), and 0.03 mg/L for NG+NL combination (84.62% abatement). The observed trend highlights the effective capacity of *Nelumbo nucifera* to remove Ni from aqueous medium, with greater efficiency when the two varieties are combined. This performance could be related to the same factors as those mentioned for iron. These results are similar to those of Rai *et al.* (2004) and Lu *et al.* (2010).



**Figure 7.** Evolution of Nickel Content during Phytoremediation

The slight efficiency observed with NG compared to NL could come from their genotypic difference. NG+NL combination shows the best results, reinforcing the hypothesis of a synergistic effect already observed for iron and other parameters. This synergy could result from a broadening of root ecological niches and a complementarity in metabolic mechanisms of absorption. These results confirm that *Nelumbo nucifera* could be successfully used for the removal of nickel from contaminated effluents, and that mixture of the two varieties optimizes the efficiency of phytoremediation process.

## Conclusion

This study evaluated the effectiveness of two varieties of *Nelumbo nucifera* (Gaertn and Lutea) in remediating wastewater from Kokumbo mining sites in Côte d'Ivoire, contaminated by heavy metals such as iron and nickel. After 31 days, phytoremediation system implemented with experimental tanks was effective in treating wastewater. At the end of treatment, plants had alkalized the medium, improved turbidity, and significantly removed the tested heavy metals. The implemented process could therefore represent an ecologically and economically viable alternative for the sustainable management of mine waste in tropical areas.

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**Compliance with Ethical Standards:** This article does not contain any studies involving human subjects.

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