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The Efficiency of *Aspergillus niger* and *Trichoderma hamatum* for bioremediation of soil Contaminated with Nickel and Copper

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Abstract

A Laboratory experiment was carried out to study the effect of soil Inoculation with fungus for bioremediation of soil that Contaminated with heavy metals because this problem has become of great concern due to the adverse effects its causing around the world and the exposure of Iraqi soil in general and agricultural soils in particular to the pollution of heavy metals. Microorganisms have sophisticated methods that enable them to survive in the presence of heavy metals polluting the environment. The study aimed to reduce the impact of heavy metals by used fungi because its environment friendly. So, this study used two species of fungi *Aspergillus niger* and *Trichoderma hamatum* which were Isolated from agricultural soil from Al- Fao city in Al- Basrah – Iraq to soil Contaminated with three levels of copper and nickel (0.5, 1, 1.5 of critical concentration). Results showed that these two fungal isolates differ in their efficiency in removing these heavy metals from soil. The two Previous fungi were almost identical in removing nickel, but their suitability differed significantly with Copper, As *A. niger* surpassed the level and reached 85.47%. The efficiency of removing by fungal isolate decreased with the concentration level of heavy metals and It has effective removal by *A. niger* with 53.35% at third concentration. Despite the difference in the ability of the two fungi to treat the type of pollutant, and its good in bioremediation, as the contributed to reducing the percentage of pollution.

Keywords: *Bioremediation, fungi, Copper, Nickel, Incubation*

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كفاءة فطري *Aspergillus niger* و *Trichoderma hamatum* في المعالجة الحيوية للتربة الملوَّثة بالنيكل والنحاس

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الخلاصة:

أُجريت تجربة مختبرية لدراسة تأثير تلقيح التربة بالفطريات في المعالجة الحيوية للتربة الملوَّثة بالمعادن الثقيلة، إذ أصبحت هذه المشكلة محط اهتمام كبير لما تسببه من آثار سلبية في مختلف أنحاء العالم، ولا سيما تعرّض التربة العراقية عموماً والترب الزراعية على وجه الخصوص لتلوث المعادن الثقيلة. تمتلك الكائنات الحية الدقيقة طرائق متطورة تمكّنها من البقاء في وجود المعادن الثقيلة الملوِّثة للبيئة. هدفت الدراسة إلى تقليل تأثير المعادن الثقيلة باستخدام الفطريات لكونها صديقة للبيئة. وعليه، استُخدم في هذه الدراسة نوعان من الفطريات هما *Aspergillus niger* و*Trichoderma hamatum*، اللذان عُزلا من تربة زراعية في قضاء الفاو بمحافظة البصرة – العراق، لمعالجة تربة ملوَّثة بثلاثة مستويات من النحاس والنيكل (0.5، 1، 1.5 من التركيز الحرج). أظهرت النتائج أن العزلتين الفطريتين تختلفان في كفاءتهما على إزالة هذه المعادن الثقيلة من التربة. كان الفطران متقاربين تقريباً في إزالة النيكل، إلا أن ملاءمتهما اختلفت معنوياً في حالة النحاس، إذ تفوّق *A. niger* وبلغت كفاءته 85.47%. كما انخفضت كفاءة الإزالة بواسطة العزلات الفطرية بزيادة مستوى تركيز المعادن الثقيلة، وقد سجل *A. niger* إزالة فعّالة بنسبة 53.35% عند التركيز الثالث. وعلى الرغم من الاختلاف في قدرة الفطرين على معالجة نوع الملوِّث، فقد أظهرا كفاءة جيدة في المعالجة الحيوية، إذ أسهما في تقليل نسبة التلوث.

الكلمات المفتاحية :المعالجة الحيوية، الفطريات، النحاس، النيكل، التحضين.

1. Introduction

Pollution with heavy metals is increasingly becoming a problem and has become of great concern due to the adverse effects it is causing around the world. These inorganic pollutants are being discarded in our waters, soils and into the atmosphere due to the rapidly growing agriculture and metal industries, mining, smelting, improper waste disposal, fertilizers and pesticides (Blundell *et al*., 2020).

Copper is naturally present in the environment and has been widely used in industry and agriculture. Its toxicity has been known for many years So this trait was exploited by its use as a fungicide and many harmful pests (Alengebawy *et al*., 2021). Copper total natural content in soil is 20–1 mg kg^{-1} and the maximum permissible total concentration in soil is about 100 mg kg^{-1} (Kloke, 1980), The reason for the toxicity of copper is by its interference in the reactions of building and catabolism, and mainly in the disruption of specialized enzymatic reactions. (Alengebawy *et al*., 2021), Nickel is also the 22nd element in terms of its availability in the Earth's crust, as it is found in low levels in the environment, and for its distinctive property of corrosion resistance, it is used in many industrial applications. The standard limits of nickel according to European standards are 0.05 mg L^{-1} and its total concentration in agricultural soils is often between 40 and 10 mg kg^{-1} (Alengebawy *et al*., 2021).

The reclamation of soils contaminated with heavy metals is a difficult challenge. Currently, Technology at the present time resorts to digging or burying the soil, washing the soil, or by physical and chemical separation of pollutants. The cost of chemical treatment of soils is very high depending on the type of pollutants, Soil characteristics and the conditions of the site itself. There are many technological alternatives that are less expensive and environmentally friendly, and some of them use microorganisms in them as bio-fertilizers, which represents the main key to the bioremediation process. Although mineral pollutants cannot be easily removed from soil and disposed of through fertilizer, However, they can be converted into organic groups that are biologically less effective than mineral substances. Bioremediation refers to the use of organisms (plants, bacteria and fungi) in the treatment and removal of toxic pollutants (organic and inorganic materials and heavy metals) from agricultural soils, contaminated water and landfills as the best methods Modern treatment compared to other methods (Arora & Khosla,2021), Microorganisms have sophisticated methods that enable them to survive in the presence of heavy elements polluting the environment. The bio cell wall consists of polysaccharides, lipids, proteins and compounds with active aggregates that bind heavy metal ions. These groups include carboxylates, hydroxyl, amines and phosphate groups (yang *et al*., 2024). Bacteria and fungi also depend on the involvement of different internal and external enzymes in binding of heavy metal ions (Karigar *et al*. 2011). Fungal treatment is a form of bioremediation that uses fungi to eliminate or control the proportion of pollutants in the environment, by increasing the biomechanical activity and the effectiveness of enzymes, as fungal yarn works to reduce the proportion of toxins in the original position, and some types of fungi have the ability to absorb heavy metals and increase their concentration in Mushroom bodies (Goutam *et al*., 2021).

Due to the exposure of Iraqi soils in general and agricultural soils in particular to the pollution of heavy metals, the study aimed to reduce the impact of heavy metals in biological activity using different species of locally isolated fungi, by determining the efficiency of the fungal species used in the study to reduce the harmful impact of pollution with heavy metals.

2. Materials and Methods

The soil sample were taken from an agricultural area in Al-FAO in Basra governorate from the surface layer (0-30 cm). It placed in plastic bags, brought to the laboratory, and part of them was dried airily to perform the preliminary analyzes including the physical, chemical and biological properties of the soil as shown in table (1), The remaining part of the soil was kept at -20 C for subsequent biological experiments.

Table 1: Physical, chemical, and biological properties of the soil

Measurements or characteristics	Units used	Value
Electrical conductivity (Ec)	ds m^{-1}	5.60
Degree of soil reaction (PH)	-	7.54
Organic matter	mg kg^{-1}	2.37
Total solid carbonates	%	37.00
Cation exchange capacity (CEC)	Centi mole $^{+}$ kg^{-1}	16.15
Organic carbon	mg kg^{-1}	1.38
Total nitrogen		0.14
Nickel (Ni)	mg^{-1}	0.00
Copper (Cu)		0.05
Number of Bacteria	Cfu g^{-1} soil	2.89*108
Number of fungi		1.60*105
Sand	%	13,70
Silt		45,62
Clay		40,68
Soil Texture	-	Silty Clay

2.1. Availability of heavy elements in soil:

Heavy metals concentration in the soil were measured according to (Lindsay & Norvel,1978), By weighing 15g of dry soil aerobically with the addition of 30 ml of extraction solution consisting of [3.93 gm Diethylene triamine penta acetic acid (DTPA)+ 2.94 gm Calcium chloride (CaCl2.2H2O) + 30 ml Triethanol amine solution (TEA) The volume is supplemented to two liters], The suspension was shaked for 2 hours using a mechanical shaker and after the shaking has expired, The pH of the Suspension solution, Was measured the EC with the filtrate and The heavy elements were sprayed with filtrate Cu and Ni by the atomic absorption device (Atomic absorption

Spectrophotometer Phoenix- 986) In the Central Laboratory of the College of Agriculture / University of Basrah.

The percentage of the efficiency of fungi isolated in removing heavy elements were calculated by the following:

1. Calculating the fixed quantity = (available in the soil at the beginning of the experiment - available in the soil at the end of the experiment).

2. Calculation of the percentage of innate efficiency in removal elements = (fixed / total available) * 100%.

2.2 Soil preparation:

250 g of soil was placed in clean glass containers. Soil models were contaminated with nickel and copper salts at a concentration of 0 (C0), 0.5 Critical Concentration (C1), Critical Concentration (C2), 1.5 Critical Concentration (C3) for each element as shown in Table 2 and Critical Concentration was adopted according to Kloke, (1980).

TABLE 2. Levels of contamination soil with heavy elements (mg kg-1).

Concentration			C0	C1	C2	C3
Ietal	Salt used	mical salt symbol	0%	50% tical level	100% tical level	150% ical level
Ni	ckel chloride	NiCl2.6H2O	0.00	25.00	50.00	75.00
Cu	opper sulfate	CuSO4.6H2O	0.00	50.00	100.00	.50.00

By dissolving the specific weight of salt in a quantity of water equivalent to the field capacity of the soil was maintained moisture field capacity by compensating the weight difference during the duration of the experiment.

2.3 Isolation and purification of fungi:

Fungal isolate (*Aspergillus niger* and *Trichoderma hamatum*) were isolated in the Plant Protection Department / College of Agriculture / University of Basrah, And purified by several cultures (Sub cultures) several times in the Potato Dextrose Agar which prepared by taking 200 g of peeled and chopped potatoes and boiled with Half a liter of water, Then mashed and filtered by gauze, Then added to the filtrate 10 g of dextrose and 20 g of acres and the volume was completed to a liter and the antibiotic Chloromphenical concentration of 250 mg L^{-1} was added and its pH was adjusted to 5.5, Medium was sterilized by Autoclave at 121 ° C and 15 lb^{-2} pressure for 20 minutes, and The medium was inoculated with isolated fungi, Incubated at 28 ± 2 °C, for 3 days and returned to the purification process Until completely pure colonies are obtained (Pitt & Hocking, 1997).

2.4 Measurement the tolerance of fungal isolates toward for heavy metals:

The efficiency of the isolated fungi was tested by growing it (PDA) medium contaminated with heavy metals namely nickel and copper at the maximum studied concentration (150% critical concentration), Incubated at 2±28 °C for five days, Then the fungal efficiency was tested by measuring the diameter of the fungal colony, according to the following equation:

$$\text{Colony diameter} = \text{The total length of two perpendicular diameter} / 2$$

2.5 Preparation of fungal Inoculum:

Fungal Inoculum was prepared by through the growth of these isolates in the food medium Potato Dextrose Broth by adding 0.5 cm diameter tablets of pure colonies to the sterile liquid food medium and incubated at 28 °C ±2 for five days.

2.6 Soil pollination:

2% of sterile organic matter (cattle residue) was autoclaved under 121 °C, 15 pound ang-2 with soil and inoculated with pure fungal farms at 5-day-old liquid at 20 ml per container with a soil density of 40 * 10^3 CFU gm^{-1} soil, Leaving untreated treatment for each contamination of heavy metals, All incubated at 28 °C ±2 for 63 days, Taking into account the stirring of the soil for ventilation during the experiment period.

2.7 Calculate the numbers of total fungi and total bacteria:

The numbers of total fungi and bacteria were calculated in soil treatments by dilution and counting method in (Plate Count) dishes. Using PDA for Fungal Growth and Nutrient Agar for Bacteria Growth, 1 g of treated soil was added to 9 ml of sterile water to get dilution 10^{-1}, Serial dilutions were done then until 10^{-8}. Take 1 ml of the10^{-3} dilution for the fungi count and 1 ml of the 10^{-6} dilution for the bacterial count and They were added to sterile Petri dishes, The special food medium was poured on it and the dishes were moved in a gentle manner and left until it hardened, The Petri dishes were incubated at 28 ± 2 °C and The dishes for bacteria were incubated at 30 °C, The numbers of developing colonies were calculated in each plate after 5 days of incubation Considering that each colony results from the growth of one cell (Pitt & Hocking, 1997) As:

$$\text{Number of colonies per 1 g of dry soil} = \frac{\text{No. of colonies per plate * Inverted dilution}}{\text{Dry soil weight}}$$

3. Results and Discussion

1 The growth of fungal isolates in media contaminated with heavy metals:

Table (3) shown the efficiency of *T. hamatum* and *A. niger* fungal isolates to growth in media contaminated with heavy metals. Average colony diameter obtained was 2.68 cm and 2.39 cm for these isolates, respectively. The medium contaminated with nickel (Ni) gave the highest growth diameter of *T. hamatum* (4.35 cm), The reason may be that this fungus absorbs Nickel biologically due to its high ability to bind these elements with the functional groups (Lin *et al*., 2005).The medium contaminated with copper (Cu) gave the highest growth diameter of *A. niger* (4.42 cm), The reason for the difference in growth may be due to the difference in the sensitivity of the fungi and the extent of its resistance to growth under conditions of heavy metals contamination, Came in agreement with Al-abedi, (2023) who found that *A. niger* isolates were resistant to soils treated with copper.

Table 3: Diameter of the growing fungal colony (cm) in contaminated Soil with 150% of the critical concentration of heavy Metals.

Metal	Ni	Cu	Mean
erma hamatum			
illus niger			

3.1. Fungal removing efficiency of heavy metals in contaminated soil:

It is noted from Table (4), that both *A. niger* and *T. hamatum* have shown a high ability to reduce the availability of copper (Cu) and nickel (Ni) in contaminated soil after an incubation period of 63 days. Nickel, however, was almost completely removed at the lower concentrations C1 and C2. Its quantity decreased from 25 and 50 micrograms/gram of soil to 0.00 micrograms/gram for both fungi. However, at the highest concentration of nickel (C3), the superiority of the fungus *A. niger* was observed, as its concentration decreased from 75 micrograms/gram of soil to 4.48 micrograms/gram of soil. Regarding copper, a gradual decrease in its availability was observed, and although the removal of copper was less than the removal of nickel, the two fungi were able to reduce its availability compared to its initial levels. And as shown in Table (5), the nickel removal efficiency exceeded 98% for both fungi. Meanwhile, the efficiency of copper removal ranged between 64–66%. Overall efficiency was higher in *T. hamatum* (98.29%) compared to *A. niger* (98.01%), These results confirm the high potential of fungal isolates in the bioremediation of heavy metals, especially nickel, Because of their high ability to removing heavy metal of soils contaminated by various biomechanical mechanisms, As well as soil factors that may have helped to increase the fungi tolerance of heavy metals in the soil, that's return to that Fungi can be developed easily, produce high yield of biomass, and can easily be genetically and morphologically manipulated. Fungi appear high resistance to the large amount of heavy metals and simultaneously can accumulate micronutrients (Cu, Zn, Ni, Co and Mn) and non-nutrient metals (Cd, Pb, Hg and Ag). Cell wall of fungi is composed of chitin, lipids, mineral ions, polysaccharides, polyphosphates, and proteins. Several mechanisms were included in heavy metal bioremediation by fungi as they could degrade heavy metal ions by extracellular and intracellular precipitation, energetic uptake or by converting the valency of the meta ions, many fungi also can accumulate metals into their spores and mycelium (Xie *et al*., 2016). In particular *T.hamatum*, which binds nickel ions to biopolymers, especially in Peptidoglycan and the outer cell wall.

Table 4: the fourth interaction between elements, Concentration, and Incubation on the availability of the heavy metals in soil (μg g^{-1} soil) at the beginning and end of the experiment.

Fungus		lable at the beginning riment before add the vaccine	ailable at the end of the experiment (63 days)	
Elements	**Con.**		*A. niger*	*T. hamatum*
Ni	**C1**	25.00	0.00	0.00
	C2	50.00	0.00	0.00
	C3	75.00	4.48	3.85
Cu	**C1**	51.45	7.48	14.98
	C2	101.45	45.92	31.21
	C3	151.45	70.65	61.28
N.S				

Table 5: Percentage (%) of fungal efficiency in the removing of heavy metals of soil.

Metal	*A. niger*	*T.hamatum*	Mean
Ni	98.01	98.29	98.15a

Cu	64.57	66.55	65.56d
Mean	81.29	82.42	

Table (5) shows the difference in the efficiency of the fungal isolates in the representation of heavy elements and reduce their availability in soil, as *A. niger* in the proportion of the representation of heavy metal in contaminated soil (%) compared to *T. hamatum* (82.42%) and these results are consistent with (Gomes *et al*., 1999) which indicates that *A. niger* are highly capable of removing heavy metals, including gold, silver, iron, zinc and copper and depositing them on the cell wall.
Table (5) shows the variation of the innate efficiency in the representation of different heavy metals used, the highest efficiency was in the presence of nickel, which was 98.29% at fungal pollination while *T.hamatum* gave the lowest efficiency in the presence of copper, which was 64.57% and 66.55% when fungus *A.niger* and *T.hamatum,* was used respectively, and this may due to absorption of these elements with different absorption mechanisms and convert into organic complexes within living cell tissue and the efficacy of fungal bioremediation is demonstrated in its ability to degrade persistent organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and petroleum hydrocarbons, as well as to immobilize and transform heavy metals through biosorption and bioaccumulation (Dinakarkumar *et al*., 2024), Innate efficiency can be arranged In the representation of different heavy metals used in the following sequence:

- *A. niger*: Cu < Ni
- *T. hamatum*: Cu < Ni

As shown in Table (6) The decrease in the ability of the studied fungi to represent heavy metals by increasing their concentrations for both fungi, where the highest representation was at the first and second level until it reached 100% with nickel element, and the proportion of representation at the third level of pollution was decrease especially with copper. The increased of the contamination reduce their innate efficiency by inhibiting the growth of microorganisms in the soil and the diverse effects that these metals depend on individual groups of microorganisms result from specific physiological, morphological and genetic characteristics (Wyszkowska *et al*., 2013). Copper also adversely affects the production of fungal blackboards and increases its negative effect by increasing its levels (Ayad *et al.* 2018), Rilling *et al.* (2020) indicates that copper reduces microbial biomass and its diversity and the effect increases as the level of pollution increases.

Table 6. Effect of Pollution Level on Instinctive Efficiency in removing Heavy Metals.

metal	**Con.**	***A. niger***	***T.hamatum***
Ni	**C1**	100.00 a	100.00 a
	C2	100.00 a	100.00 a
	C3	94.03 abc	94.87 abc
Cu	**C1**	85.47 cd	70.36 e
	C2	54.88 f	69.76 e
	C3	53.35 f	59.53 f

4. Conclusion

The study demonstrates that Fungal isolates t from unpolluted agricultural areas have the ability to adapt to growth in soils contaminated with heavy metals. Contamination of the soil with heavy metals (Ni and Cu) reduced the number of fungi compared to the non-contaminated comparison treatment. And A. *niger* and *T. hamatum* varied in their ability to grow in soils contaminated with heavy metals and the two Previous fungi were almost identical in removing nickel, but their suitability differed significantly with Copper, As *A. niger* surpassed the level and reached 85.47%. The efficiency of removing by fungal isolate decreased with the concentration level of heavy metals and it has effective removal by *A. niger* with 53.35% at third concentration.

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4.2. Contributions of authors

H.T.H.: Study conception and design, experimental setup and execution, data collection and analysis, statistical analysis, manuscript drafting and writing, and submission of the final manuscript.

M.M.N.: Study design and methodology planning, supervision of experimental work, data interpretation, manuscript review and revision, and approval of the final version.**]**

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4.3. Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this research. No competing financial, professional, or personal interests that could have influenced the work are reported.

5. References

Al-Abedi, H. F. H. (2023). GC-MS analysis of the compounds produced from two species of *Penicillium*. *Basrah Journal of Veterinary Research*, 22(1). https://doi.org/10.23975/bjvetr.2023.178294

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, 9(3). https://doi.org/10.3390/toxics9030042

Arora, V., & Khosla, B. (2021). Conventional and contemporary techniques for removal of heavy metals from soil. In *Biodegradation Technology of Organic and Inorganic Pollutants*. IntechOpen. https://doi.org/10.5772/intechopen.98569

Ayad, F., Matallah-Boutiba, A., Rouane-Hacene, O., Bouderbala, M., & Boutiba, Z. (2018). Tolerance of *Trichoderma* sp. to heavy metals and its antifungal activity in Algerian marine environment. *Journal of Pure and Applied Microbiology*, 12(2), 855–870. https://doi.org/10.22207/JPAM.12.2.48

Blundell, R., Briffa, J., & Sinagra, E. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*, 6(9), e04691. https://doi.org/10.1016/j.heliyon.2020.e04691

Dinakarkumar, Y., Ramakrishnan, G., Gujjula, K. R., Vasu, V., Balamurugan, P., & Murali, G. (2024). Fungal bioremediation: An overview of the mechanisms, applications and future perspectives. *Environmental Chemistry and Ecotoxicology*, 6, 293–302. https://doi.org/10.1016/j.enceco.2024.07.002

Gomes, N. C. M., Rosa, C. A., Pimental, P. F., Linardi, V. R., & Mendonça-Hagler, L. C. S. (1999). Uptake of free and complexed silver ions by yeasts isolated from a gold mining industry in Brazil. *Journal of General and Applied Microbiology*, 45, 121–124. https://doi.org/10.1590/S1517-83822002000100013

Goutam, J., Sharma, J., Singh, R., & Sharma, D. (2021). Fungal-mediated bioremediation of heavy-metal–polluted environment. In *Microbial Rejuvenation of Polluted Environment: Volume 2* (pp. 51–76). Springer Singapore. https://doi.org/10.1007/978-981-15-7455-9_3

Karigar, C. S., Chandrakant, S., & Rao, S. S. (2011). Role of microbial enzymes in the bioremediation of pollutants. *Enzyme Research*, 2011, Article ID 805187. https://doi.org/10.4061/2011/805187

Kloke, A. (1980). Richtwerte für tolerierbare Gesamtgehalte einiger Elemente in Kulturböden. *VDLUFA*, H2, 9–11. https://doi.org/10.22194/JGIAS/12.11

Lin, Z., Wu, J., Xue, R., & Yang, Y. (2005). Spectroscopic characterization of Au^{3+} biosorption by waste biomass of *Saccharomyces cerevisiae*. *Spectrochimica Acta Part A*, 61, 761–765. https://doi.org/10.1016/j.saa.2004.03.029

Lindsay, W. L., & Norvell, W. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, 42(3), 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

Pitt, J. T., & Hocking, A. D. (1997). *Fungi and Food Spoilage*. Academic Press, London, 405 pp. https://doi.org/10.1016/j.saa.2004.03.029

Rillig, M. C., Golubeva, P., Ryo, M., Muller, L. A. H., Ballhausen, M. B., Lehmann, A., & Sosa-Hernández, M. A. (2020). Soil saprobic fungi differ in their response to gradually and abruptly delivered copper. *Frontiers in Microbiology*, 11. https://doi.org/10.3389/fmicb.2020.01195

Wyszkowska, J., Kucharski, J., Borowik, A., & Kucharski, M. (2013). Effect of cadmium, copper and zinc on plants, soil, microorganisms and soil enzymes. *Journal of Elementology*, 18(4), 769–796. https://doi.org/10.5601/jelem.2013.18.4.455

Xie, Y., Fan, J., & Zhu, W., *et al.* (2016). Effect of heavy metals pollution on soil microbial diversity and bermudagrass genetic variation. *Frontiers in Plant Science*, 7, 1–12. https://doi.org/10.3389/fpls.2016.00755

Yang, Z., Zhao, B., Tang, H., Xiang, G., & Xiao, W. (2024). Microbial mediated remediation of heavy metals toxicity: Mechanisms and future prospects. *Frontiers in Plant Science*, 15. https://doi.org/10.3389/fpls.2024.1420408