POUL DUE JENSEN / GRUNDFOS FOUNDATION

FOOD SUPPLIES UNDER STRESS FROM POLLUTION AND DROUGHT

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Abstract

The global rise in population intensifies the need for sustainable and safe food production, particularly in regions where irrigation relies on heavy metal-contaminated water. This study investigates the uptake of heavy metals by different crop to identify those best suited for cultivation under heavy metal-polluted conditions. Through a series of growth experiments, soil and water analyses, and advanced elemental detection using ICP-MS, it is assessed how various crops absorb toxic metals such as copper, lead, cadmium, and zinc. Results reveal that heavy metal accumulation varies significantly by plant species and part, with root vegetables like potatoes demonstrating the lowest uptake in the edible part. Moreover, environmental factors and growth conditions - particularly irrigation practices - influence metal absorption. Results suggest that non-optimal growth conditions may help reduce heavy metal uptake. Although water and soil samples from both Tanzania and Denmark generally complied with regulatory limits, the accumulation in plants is so high that consuming just a few grams of the crops lead to exceeding the weekly intake thresholds. This study forms the basis for a set of guidelines that prioritize root crop cultivation, adapt irrigation practices, and identify which parts of the plant are safest to consume in order to minimize exposure to heavy metals

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Introduction

The growing global population puts increasing pressure on the world's resources, especially food production. This strain is intensified in areas where heavy metal-contaminated water is used for irrigation, leading to the accumulation of toxic metals in crops. This threatens agricultural productivity and the consumers health, making it more difficult to ensure safe and sustainable food production. This study aims to investigate the uptake of heavy metals by crops from contaminated soil and water, with the goal of identifying crops that can be optimally cultivated under heavy metal-polluted conditions. Crops with reduced heavy metal accumulation could play a crucial role in enhancing food safety and improving public health for affected populations.

Research question

Which crop species are least prone to heavy metal accumulation, and how can this knowledge be applied to enhance public health in regions where irrigation with heavy metal-contaminated water is unavoidable?

Theory behind the project

Occurrence of heavy metals in the environment

Heavy metals enter soil through both natural processes and human activities such as mining, transport, agriculture, and wastewater use[1]. Although trace amounts of metals such as zinc and copper are essential for biological processes, elevated concentrations can be detrimental to plants, animals, and humans. Unlike organic pollutants, heavy metals persist in the environment and bioaccumulate through the food chain [2]. Heavy metal contamination is a particularly pressing issue in Africa, where elevated levels of toxic metals have been detected in soil, plants, animals, and water. In Nigeria, concentrations of lead and cadmium have been found in crops such as cucumber, cabbage, banana, and eggplant, exceeding the permissible limits set by the WHO[3]. This clearly highlights the extent and severity of the issue. Additionally, mining operations release significant amounts of metals such as zinc, lead, cadmium, and nickel, which contaminate surface water, groundwater, soil, and food sources[4].

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[1] (Wan, Zhuang, Wang, & Li, 2023)
[2] (Hunding & Gram, 2024)
[3] (Sobukola , O.E., O.M. , & A.A. , 2010)
[4] (Okereafor, et al., 2020)

Phytoremediation

Phytoremediation is a method for removing heavy metals from soil, utilizing hyperaccumulators that absorb large quantities of specific metals and thereby contributes to soil decontamination. However, this approach is resource- and time-intensive, and it is ineffective when heavy metals are continuously added through irrigation water. This limitation highlights the need for a more sustainable and comprehensive solution[5].

Health Effects of Heavy Metal Ingestion

Consumption of heavy metals via contaminated crops can have severe consequences for human health. The body attempts to excrete these metals, but some accumulate in tissues and can cause damage. Accumulated metals can disrupt enzymatic functions and generate harmful free radicals. Heavy metals may also impair the nervous system, leading to memory and concentration difficulties. Heavy metals place strain on the cardiovascular system, increasing the risk of hypertension and heart disease. These metals also accumulate in the kidneys, potentially causing renal damage and chronic kidney disease over time. Chronic exposure of heavy metals further elevates cancer risk through mechanisms like direct DNA damage (mutagenesis)[6]. These findings underscore the serious health risks and the importance of preventing heavy metal consumption through crops.

Hypothesis

Based on current knowledge of how plants absorb and accumulate heavy metals, it is expected that root vegetables, such as potatoes and carrots, will contain lower concentrations of heavy metals in their edible parts compared to crops like cress and pointed cabbage, where the parts above the ground are consumed. Therefore, crops with edible underground-parts may represent a safer food source when grown in contaminated soil or irrigated with heavy metal contaminated water. It is expected that the uptake of heavy metals is also influenced by factors such as soil conditions, climate, the specific type of heavy metal, and plant-specific uptake mechanisms. It is further assumed that the level of heavy metals plants can accumulate without harming the food chain depends on the toxicity and properties of each metal.

[5] (A Citizen's Guide to Phytoremediation, 2012)
[6] (tungmetalbelastning, u.d.)

Methods

To address our research question, we employed both experimental and theoretical methods to investigate heavy metal uptake in plants as well as heavy metal presence in soil samples. Our experimental design was based on existing research while aiming to answer questions that previous studies have not addressed. Our experiments can be categorized into the following main areas:

1. **Growth experiments** – Investigating how different heavy metals affect plant growth and how growth conditions influence heavy metal uptake.
2. **Detection of heavy metals in soil** – Identifying heavy metals in soil samples using precipitation reactions and colorimetric analyses.
3. **Water sample analysis** – Testing heavy metal content in water samples from Tanzania to investigate the presence of heavy metals in the water.

Experiment 1 - Pilot experiment

Purpose: The purpose of this experiment was to investigate the uptake of heavy metals by various crop species and to assess the impact of these metals on plant growth, before making a final selection of crops and refining the methodology for a full-scale study.

Experimental Setup: Fast-growing plant species were selected to allow for timely observation of heavy metal uptake. A diverse range of crops from different botanical families was included, due to variations in plant physiology such as root morphology and leaf structure, which may influence the capacity for heavy metal absorption and tolerance. Root vegetables were incorporated to evaluate whether subterranean plant parts exhibit lower heavy metal accumulation and are more suitable for consumption.
<u>Crops Included</u>: Garden cress, pointed cabbage, parsley, arugula, carrots, and potatoes
<u>Heavy Metals Applied</u>: Copper sulfate ($CuSO_4$), Lead nitrate ($Pb(NO_3)_2$), and Zinc nitrate ($Zn(NO_3)_2$)

Methodology:

Six beakers were prepared for each plant species, each filled with an appropriate volume of soil under controlled conditions. Seeds were sown and lightly covered with soil in small beakers, while whole potatoes were planted in larger beakers. All beakers were irrigated with demineralized water and sealed with plastic film to simulate a greenhouse environment. After three days, once germination was observed, the film was removed, and heavy metals were added at concentrations just below the Danish regulatory threshold values (see figure 1).

Group	Lead nitrate 0.1 M	Copper sulfate 0.1 M	Zinc nitrate 0.1 M	Negative control (demi-water)	Negative control (demi-water)	Osmosis control (NaCl 0.5%)
100 mL beakers	420 µL	1560 µL	1190 µL	3000 µL	3000 µL	3000 µL
1000 mL beakers	3630 µL	13500 µL	10200 µL	25000 µL	25000 µL	25000 µL
Demineralized water added (100 mL)	2580 µL	1440 µL	1810 µL	0 µL	0 µL	0 µL
Demineralized water added (1000 mL)	21370 µL	11500 µL	14800 µL	0 µL	0 µL	0 µL

Figure 1: Distribution of plant groups. There is one of each crop in every group

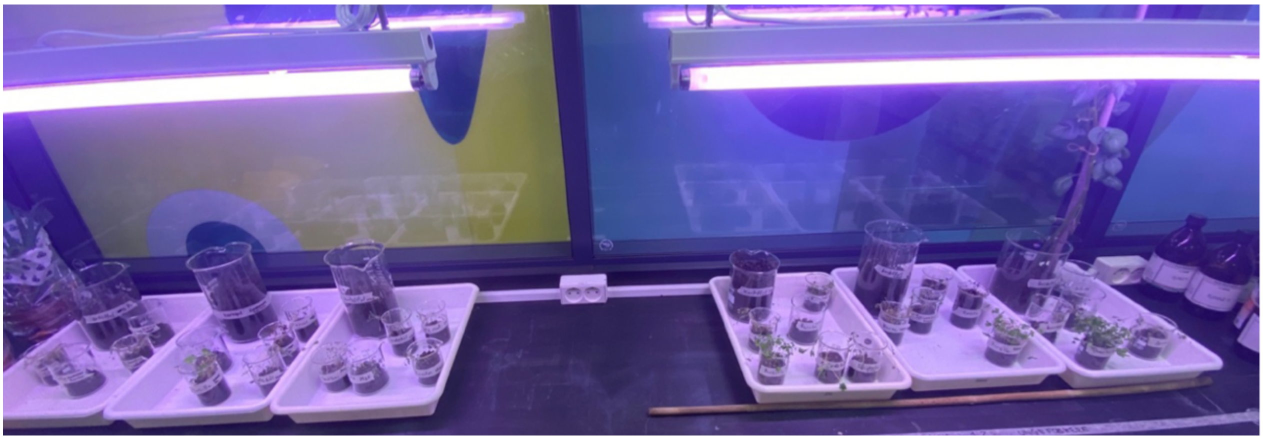


Figure 2: Experimental setup

Results:

Cabbage, arugula, and cress were fully germinated, while only a few carrot and parsley seedlings had emerged. No signs of sprouting were observed in the potatoes other than in the lead group. Copper and zinc have shown a clearly detrimental effect, particularly on cress, which quickly wilted and showed signs of damage; most plants in these groups died. In contrast, plants in the lead nitrate treatment group exhibited vigorous growth, and this group was the only one in which a potato sprouted. All plants in the lead-group displayed healthy growth with robust, green foliage. Cabbage maintained stable growth across all groups, reflecting its known capacity of heavy metals as a hyperaccumulator (results below in figure 3-8).

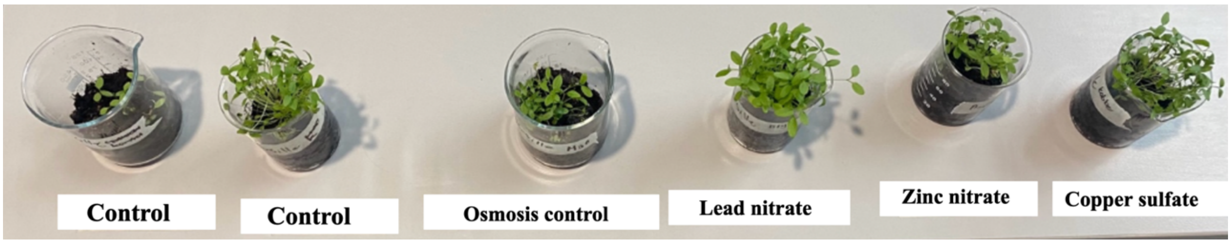


Figure 3: Results from parsley exposed to different heavy metals

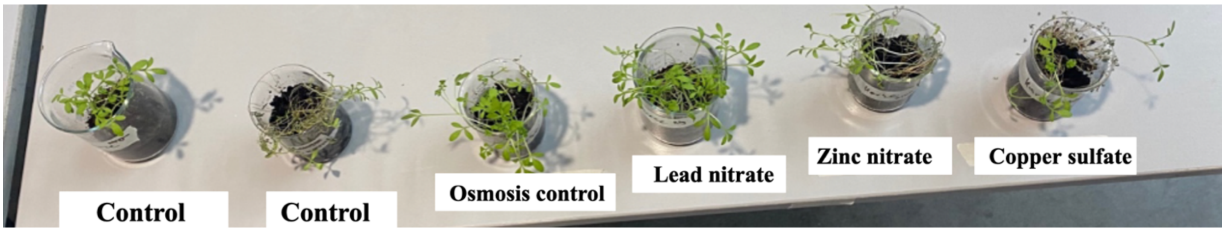


Figure 4: Results from cress exposed to different heavy metals

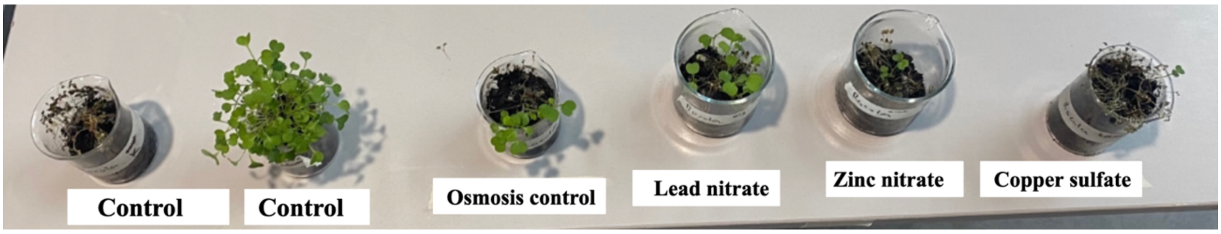


Figure 5: Results from arugula exposed to different heavy metals

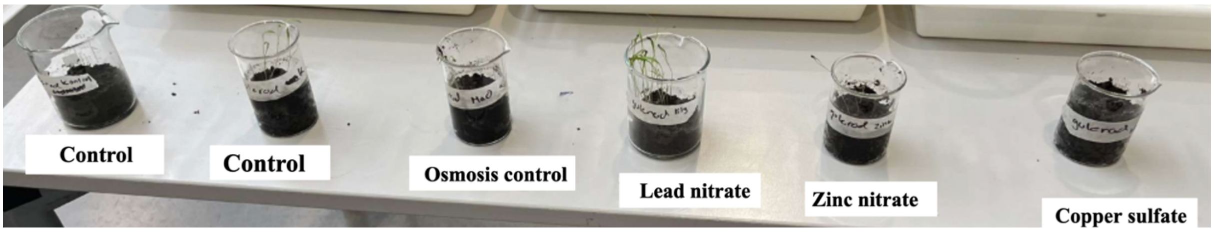


Figure 6: Results from Carrot exposed to different heavy metals

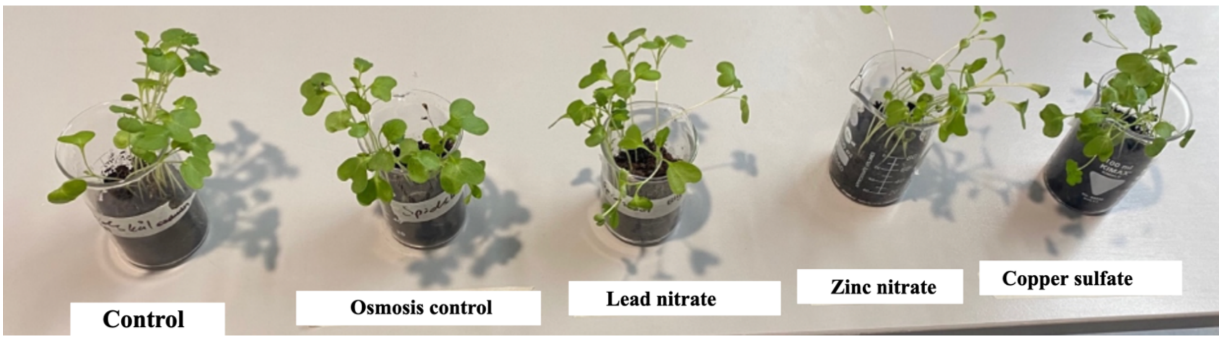


Figure 7: Results from point cabbage exposed to different heavy metals

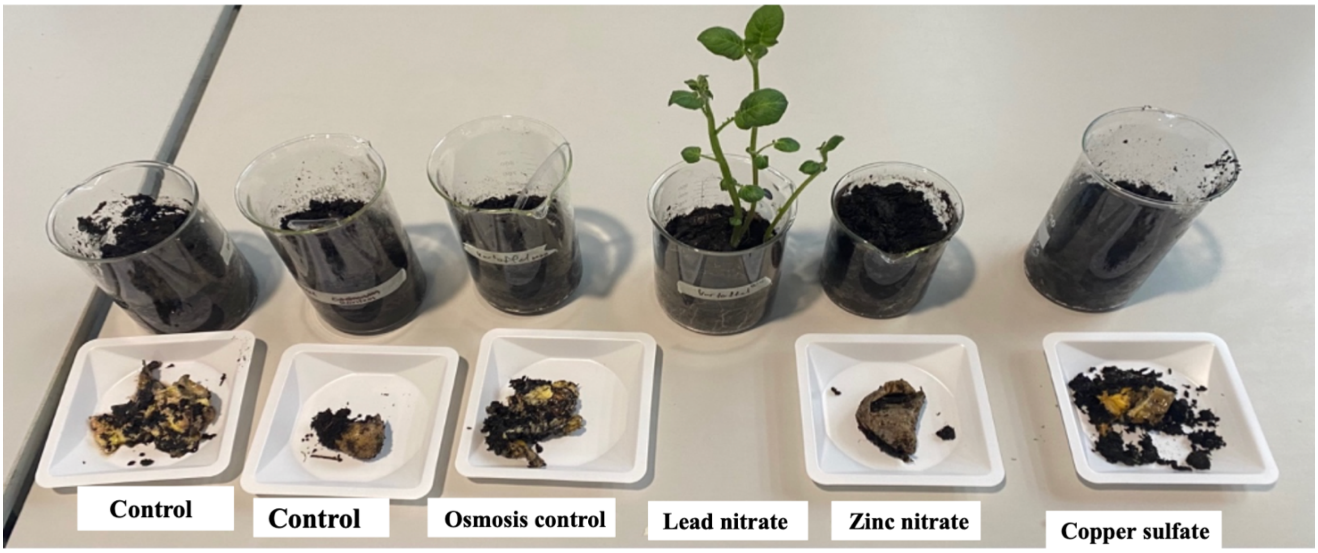


Figure 8: Results from potatoes exposed to different heavy metals

Experiment 2 - Soil Analysis

Purpose: The purpose of this experiment is to determine the concentration of heavy metals in soil samples. This information will serve as a basis for further experiments to assess whether heavy metal levels in Danish soil are sufficient to pose potential health risks.

Experimental setup: The heavy metal content in soil samples from Aarhus was investigated, primarily focusing on areas classified as contaminated according to reports from the Danish Environmental Protection Agency. Samples were collected from various locations in Aarhus: Vikjærsvej, Lokesvej, Aarhus Ø, Aarhus Harbor, a railway and a reference sample from a field in Studstrup. The samples were dried, powdered, and treated with nitric acid to release the metals. The resulting mixture was filtered. Afterwards sodium hydroxide was added to precipitate the heavy metals for detection. Initial trials failed to produce precipitates, prompting further testing to identify procedural errors, including heating methods and filtration, but no improvements were observed. Evaporation tests showed no detectable copper presence. Control tests, mixing copper sulfate with sodium hydroxide, confirmed the validity of the precipitation method.
<u>Control 1</u>: Repeated the procedure but omitted filtration. Sampled the unfiltered liquid with a spoon, added 5 mL sodium hydroxide, waited 30 seconds for results. No precipate was observed.
<u>Control 2</u>: Took a soil sample from copper sulfate group form the pilot experiment, where copper had been deliberately added to the soil. Repeated the procedure, then added 5 mL sodium hydroxide, waited 30 seconds for results, no precipitate.

Control 3: Mixed 0.1 M copper sulfate with 5 mL 2 M sodium hydroxide in a petri dish, waited 30 seconds for results. Precipitate was present.

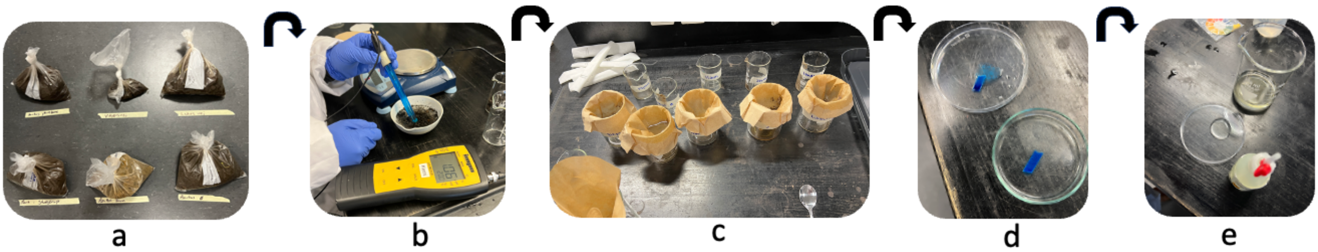


Figure 9: Image of self-designed and revised precipitation experiment to assess the presence of heavy metals in soil samples. (a) Soil samples collected from contaminated areas, (b) Nitric acid is added to release the metals, (c) The soil sample is filtered to remove solid particles, (d) The procedure is being revised, (e) Testing if the precipitation reaction results in precipitate formation.

Results:

Following filtration of the extracted liquids from the soil samples, distinct color differences were observed. The sample from the railway site exhibited a pronounced orange hue. Samples from Lokesvej, Aarhus Ø, Studstrup Mark, and Vikjærsvej displayed a more turbid orange-beige color, while the sample from Aarhus Harbor appeared cloudy with a yellowish tint. The railway showed the clearest orange. No visible precipitate was formed during the precipitation test for heavy metal detection in the soil, so the presence of copper could not be confirmed.

Experiment 3 - Soil Analysis Colorimetry

Purpose: The purpose is to obtain quantitative results for the heavy metal content in the soil samples using a colorimeter, as the precipitation test could not confirm the presence of heavy metals.

Experimental Setup and Procedure: Demineralized water and nitric acid were added to the collected soil samples to release copper ions. The solution was filtered through a coffee filter to remove larger soil particles. The samples were then divided into two test tubes: one served as a calibration sample, while a reagent was added to the other, which reacted with Cu^{2+} ions to produce a color change. Only copper was tested, as reagents for other heavy metals were not available. The copper content in all six soil samples was then measured on the colorimeter.

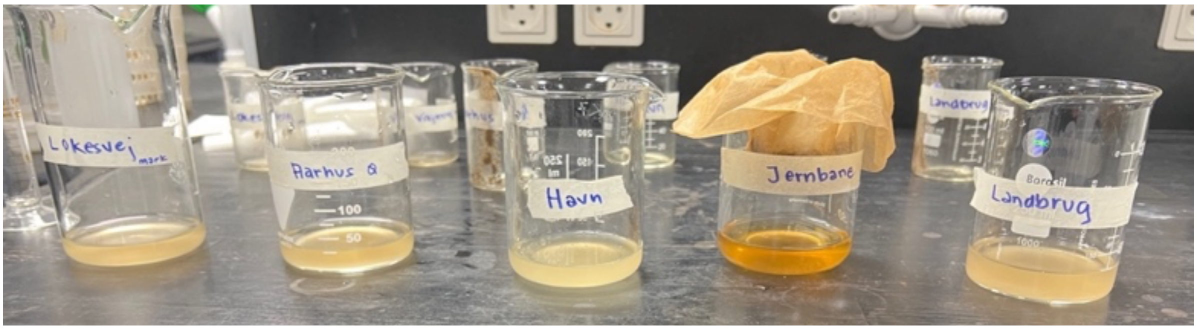


Figure 10: Soil samples after filtration ready for colorimetry analysis, where havn is harbor and jernbane is railway

Results:

These were the measured values of copper in the soil samples:

- Vikjærsvej - 0,56 mg/L
- Lokesvej - 0,87 mg/L
- Aarhus Ø - 0,33 mg/L
- Aarhus Harbor - 0,77 mg/L
- Studstrup mark - 0,54 mg/L
- The Railway - 1,45 mg/L

The values are all under the threshold values in Denmark[7].

Experiment 4 - Analysis of water samples from Tanzania

Purpose: Four water samples from different water taps used for irrigation in Bagamoyo, Tanzania, were analyzed using the Hach DR900 colorimeter. The results are intended to guide the adjustment of the growth experiment, exposing the crops to the concentration they are naturally exposed to.

Experiment setup: The analyzed water samples were collected from the area north of Bagamoyo's town center, where the RATA school is located. The samples were sourced from different water stations in the area and have therefore undergone a purification process, meaning the expected results are likely to be lower than those typically found in other regions of Africa.

Sample	Location
1	Main Gate Nianjema / MVK-School
2	Village 12 km from Bagamoyo
3	Boys dormitory/ football Fields
4	RATA School

Figure 11: The location of where the water sample were claimed

[7] (Nordværk, u.d.)

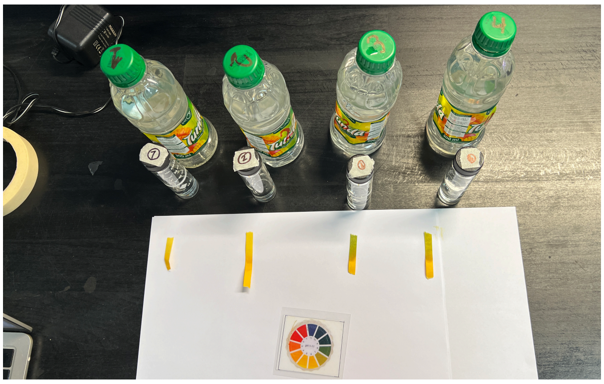


Figure 12: Water samples from Tanzania collected from sources used for irrigation

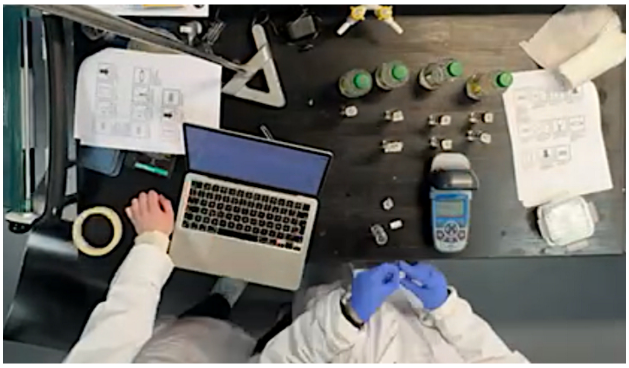


Figure 13: The testing setup for colorimetry analysis

Results:

Water sample number	1	2	3	4
Nitrite - mg/L	0,07	0,20	5,40	0,57
Fluoride - mg/L	0,00	0,27	0,55	0,15
Iron - mg/L	0,02	0,00	0,02	0,00
Manganese - mg/L	0,20	0,00	0,00	0,00
Sulphate - mg/L	13,00	4,00	60,00	3,00
Chlorine - free mg/L	0,02	0,02	0,00	0,00
Chlorine total - mg/L	0,00	0,04	0,08	0,02
Copper - mg/L	0,10	0,12	0,06	0,02
pH in the sample	6,16	7,23	6,96	7,16
pH for copper reagents	5,15	5,15	5,14	5,18

Figure 14: Measured values of each matter in the water samples

None of the values exceed the threshold limits set by the WHO.

Experiment 5 - Growth experiment with the measured values of the water samples from Tanzania

Purpose: The purpose is to investigate the uptake of heavy metals by plants when crops are exposed to heavy metals in a chemical composition reflecting the concentration values obtained from water sample analyses collected in Tanzania.

Experimental Setup and Procedure: Various plant species that constitute a significant part of the food supply - millet, buckwheat, potato, and maize - were irrigated with water containing the exact concentrations of the nine substances as measured in the water samples. After the growth period, the plants were analyzed to assess both plant health and the extent to which the substances have been absorbed in quantities potentially problematic for food safety. Uptake and accumulation of the substances were measured using ICP-MS.

Matter	Average concentration mg/L
Cl (total)	0,035
Cu	0,075
F	0,24
Fe	0,01
Mn	0,5
NO_2	1,56
SO_4^{-2}	20

Figure 15: Average concentration measured in the water samples combined for plant irrigation.

Experiment 6 - Extended Growth Experiment

Purpose: This experiment investigates how varying growth conditions influence the uptake of heavy metals by plants. The aim is to understand how growth conditions affect heavy metal absorption.

Experimental Setup and Procedure: Various crops were cultivated under both optimal and constant growth conditions. Heavy metals such as lead, zinc, copper, and cadmium were added to the soil in controlled amounts. Plant growth was monitored throughout the cultivation period. After the growth phase, the plants were analyzed for heavy metal content in different plant parts using ICP-MS. The goal is to identify factors that can reduce heavy metal uptake.

Optimal growth conditions

Pot no.	Crop	Lead per pot	Cadmium per pot	Copper per pot	Nickel per pot	Zinc per pot	Temperature (°C)	Hours of light per day	Soil pH
1	Millet	0,363 mL	0	0	0	0	20	8	6,25
2	Millet	0	0,15 mg	0	0	0	20	8	6,25
3	Millet	0	0	1,35 mL	0		20	8	6,25
4	Millet	0	0	0	0,9 mg	0	20	8	6,25
5	Millet	0	0	0	0	1,02 mL	20	8	6,25
6	Millet (control)	0	0	0	0	0	20	8	6,25
7	Maize	0,363 mL	0	0	0	0	20	8	6,5
8	Maize	0	0,15 mg	0	0	0	20	8	6,5
9	Maize	0	0	1,35 mL	0		20	8	6,5
10	Maize	0	0	0	0,9 mg	0	20	8	6,5
11	Maize	0	0	0	0	1,02 mL	20	8	6,5
12	Maize (control)	0	0	0	0	0	20	8	6,5
13	Potato	0,363 mL	0	0	0	0	20	8	5,4
14	Potato	0	0,15 mg	0	0	0	20	8	5,4
15	Potato	0	0	1,35 mL	0		20	8	5,4
16	Potato	0	0	0	0,9 mg	0	20	8	5,4
17	Potato	0	0	0	0	1,02 mL	20	8	5,4
18	Potato (control)	0	0	0	0	0	20	8	5,4
19	Buckwheat	0,363 mL	0	0	0	0	20	10	5,75
20	Buckwheat	0	0,15 mg	0	0	0	20	10	5,75
21	Buckwheat	0	0	1,35 mL	0		20	10	5,75
22	Buckwheat	0	0	0	0,9 mg	0	20	10	5,75
23	Buckwheat	0	0	0	0	1,02 mL	20	10	5,75
24	Buckwheat (control)	0	0	0	0	0	20	10	5,57

Figure 16: Optimal growth conditions

Constant growing conditions for all plants

Pot no.	Crop	Lead per pot	Cadmium per pot	Copper per pot	Nickel per pot	Zinc per pot	Temperature (°C)	Hours of light per day	Soil pH
1	Millet	0,363 mL	0	0	0	0	22	24	5,8
2	Millet	0	0,15 mg	0	0	0	22	24	5,8
3	Millet	0	0	1,35 mL	0		22	24	5,8
4	Millet	0	0	0	0,9 mg	0	22	24	5,8
5	Millet	0	0	0	0	1,02 mL	22	24	5,8
6	Millet (control)	0	0	0	0	0	22	24	5,8
7	Maize	0,363 mL	0	0	0	0	22	24	5,8
8	Maize	0	0,15 mg	0	0	0	22	24	5,8
9	Maize	0	0	1,35 mL	0		22	24	5,8
10	Maize	0	0	0	0,9 mg	0	22	24	5,8
11	Maize	0	0	0	0	1,02 mL	22	24	5,8
12	Maize (control)	0	0	0	0	0	22	24	5,8
13	Potato	0,363 mL	0	0	0	0	22	24	5,8
14	Potato	0	0,15 mg	0	0	0	22	24	5,8
15	Potato	0	0	1,35 mL	0		22	24	5,8
16	Potato	0	0	0	0,9 mg	0	22	24	5,8
17	Potato	0	0	0	0	1,02 mL	22	24	5,8
18	Potato (control)	0	0	0	0	0	22	24	5,8
19	Buckwheat	0,363 mL	0	0	0	0	22	24	5,8
20	Buckwheat	0	0,15 mg	0	0	0	22	24	5,8
21	Buckwheat	0	0	1,35 mL	0		22	24	5,8
22	Buckwheat	0	0	0	0,9 mg	0	22	24	5,8
23	Buckwheat	0	0	0	0	1,02 mL	22	24	5,8
24	Buckwheat (control)	0	0	0	0	0	22	24	5,8

Figure 17: Constant growth conditions

Experiment 7 - Heavy metal uptake in different environments

Purpose: The study investigates whether heavy metal uptake in crops differs between Danish and Tanzanian climate conditions, aiming to identify species with lower uptake in one setting.

Experimental setup: Two environments were established to represent Danish and Tanzanian conditions. The Tanzanian environment was created in a greenhouse at 25°C with a growth lamp, while the Danish environment was simulated using a fan to cool down the temperature and a growth lamp. Heavy metals were measured at the same concentrations as used in the pilot experiment and 6. The concentration of nickel was 0.9 mg per 30 g of soil mixed with 3 mL of demineralized water.

Denmark

Pot no.	Crop	Lead per pot	Cadmium per pot	Copper per pot	Nickel per pot	Zinc per pot	Control (No heavy metal)
1	Potato	0,363 ml	0	0	0	0	0
2	Potato	0,363 ml	0	0	0	0	0
3	Potato	0	0,15 mg	0	0	0	0
4	Potato	0	0,15 mg	0	0	0	0
5	Potato	0	0	1,35 ml	0	0	0
6	Potato	0	0	1,35 ml	0	0	0
7	Potato	0	0	0	0,9 mg	0	0
8	Potato	0	0	0	0,9 mg	0	0
9	Potato	0	0	0	0	1,02 ml	0
10	Potato	0	0	0	0	1,02 ml	0
11	Potato(C)	0	0	0	0	0	0
12	Potato (C)	0	0	0	0	0	0

Danish growth conditions during cultivation - April / May / /June

Air temperature (°C)	15
Soil temperature (°C)	9
Precipitation (mm)	45
Daylight (hours)	14

Figure 18: Danish environment

Africa

Pot no.	Crop	Lead per pot	Cadmium per pot	Copper per pot	Nickel per pot	Zinc per pot	Control (No heavy metal)
1	Potato	0,363 ml	0	0	0	0	0
2	Potato	0,363 ml	0	0	0	0	0
3	Potato	0	0,15 mg	0	0	0	0
4	Potato	0	0,15 mg	0	0	0	0
5	Potato	0	0	1,35 ml	0	0	0
6	Potato	0	0	1,35 ml	0	0	0
7	Potato	0	0	0	0,9 mg	0	0
8	Potato	0	0	0	0,9 mg	0	0
9	Potato	0	0	0	0	1,02 ml	0
10	Potato	0	0	0	0	1,02 ml	0
11	Potato(C)	0	0	0	0	0	0
12	Potato(C)	0	0	0	0	0	0

Tanzanian growing conditions during cultivation – August to October

Air temperature (°C)	20
Soil temperature (°C)	15
Precipitation (mm)	80
Daylight (hours)	11

Figure 19: African environment

Figure 20: Growth chambers containing all 200 plants from experiment 5, 6 and 7

Results from experiment - ICP-MS

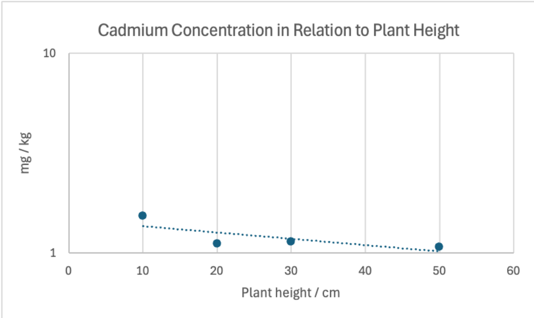
The plants from growth experiments 5, 6, and 7 were dissected and dried at 60 degrees Celsius in an incubator and then analyzed for heavy metal content using the ICP-MS method (see figure 21) at AU in collaboration with Emil Arboe Jespersen (Department of Biology, Aarhus University). The results are shown in figure 22, 23, and 24 below.

Figure 21: Set up from ICP-MS analysis

Data

Cadmium

Plant height / cm	mg / kg
10	1,53
20	1,11
30	1,14
50	1,07



Zinc

Plant height / cm	mg / kg
10	52,9
20	81,2
30	53,9
50	37,2

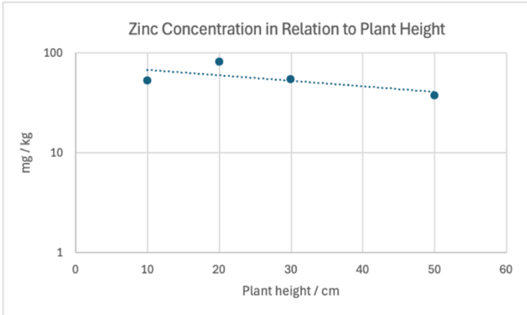


Figure 22: ***Plant Height as an Exponential Function of Heavy Metal Concentration***
The relation between heavy metal concentration in the plant stem and stem height is illustrated. The y-axis is displayed on a logarithmic scale, demonstrating that the data points approximate a straight line - supporting the presence an exponential correlation. Given the high cost and time demands of ICP-MS analysis, the number of data points per stem is limited. The concentration of heavy metals in the potato stems generally decreases with increasing height.

Metal Concentration in Plants Cadmium vs. Zinc

Plant	Cadmium mg / kg	Zinc mg / kg
Control	0,11	19,8
Water sample - leaves	4,81	88,1
Water sample - tuber	0,89	28,7

Figure 23: Results from ICP-MS analysis. Lower accumulation of cadmium and zinc is observed in the tubers compared to the leaves. Furthermore, it is evident that the plant absorbs less cadmium than zinc, as cadmium binds more strongly to the soil

Cadmium Content in Potatoes under Different Growth Conditions

Potato	Cadmium mg / kg	
Growth Conditions	Tuber	Leaves
Constant	0,49	2,87
Optimal	0,62	3,84

Figure 24:ICP-MS results indicate that, under constant growth conditions, less cadmium is absorbed compared to the optimal growth conditions for potatoes. This suggests the possibility of investigating whether growth conditions for crops can be made 'less optimal' by adjusting the water supply to reduce the absorption of heavy metals

Sources of Error

Experiment 1: Uncertainties arose from working with living plants. Poor seed quality and limited seasonal selection reduced crop diversity. Plants were grown close together, which could cause cross-contamination of heavy metals, affecting the control group. The plants were kept in a biology lab, potentially exposing them to other contaminants. No covers were used, and while no fertilizer was added, nitrate was added in a compound with lead and zinc, potentially influencing growth.

Experiment 2: Binding of heavy metals to clay and organic matter may have led to an underestimation of their concentrations in precipitation tests. Soil pH was not checked before acid addition, potentially affecting metal release. Measurement uncertainties could also have arisen during pipetting and filtering.

Experiment 4: "Chlor-total" values were illogically lower than "Chlor-free," likely due to plastic storage, delayed analysis, or sample degradation. Ideally, samples should be glass-stored, source-collected, and analyzed immediately.

Experiments 5-7: Rapid germination exposed roots, likely causing widespread plant death post heavy metal exposure. Even control plants showed stress, pointing to root damage as a factor. Cress was added to obtain supplementary data.

Discussion and Perspective

The experiments provided insight into how different plant species respond to various environmental contaminants, particularly heavy metals. While some treatments appeared to stimulate growth - possibly due to nutrient content - others had inhibitory effects, likely related to metal toxicity. Plant responses varied across species, highlighting the importance of biological differences in tolerance and uptake mechanisms. Several methodological challenges were encountered, including limited sample sizes, potential inconsistencies in seed quality, and uncertainties in chemical analysis. These factors may have influenced the results and should be addressed in future studies.

Conclusion

The experiments demonstrated that heavy metal concentrations affect plant growth differently. Copper and zinc negatively impacted crop growth, whereas lead exhibited less harmful effects. Water samples from four wells near Bagamoyo, Tanzania, showed concentrations below regulatory limits. However, when these substances were mixed into irrigation water and applied to plants, the crops absorbed a quantity of heavy metals that would limit consumption of the crops to only a few grams a week in order to stay within the maximum safe intake levels for heavy metals (TWI). The ICP-MS analysis showed that heavy metal accumulation was primarily in the leaves, with the lowest concentration found in the crop's root tuber, making it the safest part of the crop to consume based on our research. Furthermore, the ICP-MS analysis revealed that heavy metal concentrations decrease as you move higher up the plant stem. The results from the experiment indicate that growth conditions have a significant impact on the uptake of heavy metals. By altering the growing conditions to be less ideal and managing irrigation levels, it is possible to decrease the amount of heavy metals absorbed by crops. Building on these findings, guidelines can be established for countries where heavy metals are present in the soil and water used for crops:

1. Cultivate and consume root vegetables, as heavy metals accumulate to a lesser extent in these parts.
2. To reduce heavy metal uptake in plants, adjust the growth conditions by providing slightly less or slightly more water than what is optimal for the plants.
3. The higher up the plant stem, the lower the heavy metal concentration, so it is advisable to consume the upper parts of the stem."

Further Research

Building on our current findings, we aim to conduct an additional experiment focused on the post-harvest treatment of contaminated crops. The objective is to assess whether specific preparation or processing methods can reduce heavy metal concentrations to levels deemed safe for human consumption. This research will help determine whether crops contaminated with heavy metal can be made edible through processing. Such findings could potentially reduce food waste and improve food security in affected regions. The aim is to determine whether typical household or industrial food processing methods can significantly reduce heavy metal content. Additional processing techniques will also be considered and potentially incorporated into the experiment.

References

A Citizen's Guide to Phytoremediation. (2012, 9). Retrieved from epa.gov: https://19january2017snapshot.epa.gov/sites/production/files/2015-04/documents/a_citizens_guide_to_phytoremediation.pdf

Angulo-Bejarano, P., Puente-Rivera , J., & Cruz-Ortega, R. (2021, 03 27). *Metal and Metalloid Toxicity in Plants: An Overview on Molecular Aspects*. Retrieved 02 20, 2025, from PMC: https://pmc.ncbi.nlm.nih.gov/articles/PMC8066251/

Gardening Australia. (2019, 09 10). *Meet the hyperaccumulators: plants that can mine metals*. Retrieved 01 4, 2025, from Youtube: https://www.youtube.com/watch?v=GcLH6WxkVkI

Hunding, C., & Gram, N. (2024, 11 25). *Tungmetaller*. Retrieved 12 08, 2024, from Danmarks national leksikon: https://lex.dk/tungmetaller

Johnsen, I. (2013, 08 13). *Tungmetaller*. Retrieved 12 14, 2024, from Naturen i Danmark: https://naturenidanmark.lex.dk/Tungmetaller

Johnsen, I. (2013, 08 13). *Tungmetaller*. Retrieved from https://naturenidanmark.lex.dk/: https://naturenidanmark.lex.dk/Tungmetaller

Københavns Universitet. (n.d.). *Tungmetaller og skovrejsning*. Retrieved 01 04, 2025, from Grundvandet i Danmark: https://grundvandet.ku.dk/fysik/tungmetal-og-skovrejsning/

Kesari, K. K., Soni, R., Sajid Jamal, Q. M., Tripathi, P., Lal, J. A., Jha, N. K., . . . Ruokolainen , J. (2021, 5 10). *Wastewater Treatment and Reuse: a Review of its Applications and Health Implications*. Retrieved 02 18, 2025, from Springer Nature Link: https://link.springer.com/article/10.1007/s11270-021-05154-8?utm_source=chatgpt.com

Koplev, H. (2007, 11 19). *Tungmetaller*. Retrieved 02 19, 2025, from Helse: https://www.alun.dk/helse/tungmetaller.html

Miljø- og ligestillingsstyrelsen. (n.d.). *Grænseværdier for jord*. Retrieved 02 9, 2025, from Miljø- og ligestillingsstyrelsen: https://mst.dk/erhverv/rent-miljoe-og-sikker-forsyning/jord/forurenede-grunde/graensevaerdier-for-jord

Mygind, H., Nielsen, O. V., & Axelsen , V. (2010). *Basis kemi C.* Haase og søns forlag.

Nordværk. (n.d.). *Grænseværdier - forurenet jord*. Retrieved 12 29, 2024, from Norværk: https://www.avv.dk/virksomheder/graensevaerdier-forurenet-jord/

Okereafor, U., Makhatha , M., Mekuto, L., Uche-Okereafor, N., Sebola, T., & Mavumengwana, V. (2020, 03 25). *Toxic Metal Implications on Agricultural Soils, Plants, Animals, Aquatic life and Human Health*. Retrieved 02 18, 2025, from pubmed: https://pubmed.ncbi.nlm.nih.gov/32218329/

Osobamiro, T., Awolesi, O., Alabi, O. M., & Farouq, B. (2019, 08). *WHO-Maximum-Permissible-Limits-of-Heavy-Metals-in-Soil*. Retrieved from researchgate.net: https://www.researchgate.net/figure/WHO-Maximum-Permissible-Limits-of-Heavy-Metals-in-Soil_tbl3_335505667

Sloth , K. (2015, 10 15). *Marker overstiger grænseværdier for tungmetal*. Retrieved 02 14, 2025, from Dr.dk: https://www.dr.dk/nyheder/indland/marker-overstiger-graensevaerdier-tungmetal

Sobukola , P. O., O.E., K., O.M. , A., & A.A. , O. (2010, 06). *Heavy metal levels of some fruits and leafy vegetables from selected markets in Lagos, Nigeria*. Retrieved from researchgate.net: https://www.researchgate.net/publication/274380100_Heavy_metal_levels_of_some_fruits_and_leafy_vegetables_from_selected_markets_in_Lagos_Nigeria

Sturdienet. (n.d.). *Bioakkumulation og biomagnifikation*. Retrieved 12 30, 2024, from Sturdienet: https://www.studienet.dk/oekotoksikologi/bioakkumulation-og-biomagnifikation

tungmetalbelastning. (n.d.). Retrieved 02 18, 2025, from orthocare: https://orthocare.dk/tungmetalbelastning/

Wan, Y., Zhuang, Z., Wang, Q., & Li, H. (2023, 12 14). *Heavy Metals in Agricultural Soils: Sources, Influencing Factors, and Remediation Strategies*. Retrieved 12 30, 2024, from MDPI: https://www.mdpi.com/2305-6304/12/1/63

Ward Laboratories, Inc. (2024, 05 02). *Heavy Metals in Soil: Remediation Strategies*. Retrieved 12 08, 2024, from Youtube: https://www.youtube.com/watch?v=6HTRFx_xSYU