"Ananas comosus-Mediated Phytoremediation Of Heavy Metals: A Comprehensive Analysis Of Metal Uptake, Physico-Chemical Parameters, And Soil Quality"

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Abstract
Soil contamination with heavy metals poses a formidable environmental challenge. This pioneering study unlocks the phytoremediation potential of Ananas comosus (pineapple) in mitigating copper (81.2%), lead (87%), chromium (70.4%), arsenic (63.87%), cadmium (75.1%), and nickel (67.4%) pollution. Our findings reveal remarkable reductions in heavy metal concentrations, with Ananas comosus demonstrating exceptional efficiency in removing these toxic pollutants. A comprehensive analysis of soil parameters (pH, organic matter, and nutrient content) sheds light on the intricacies of phytoremediation. This groundbreaking research heralds Ananas comosus as a promising solution for sustainable soil decontamination, paving the way for innovative phytoremediation strategies.

Keywords: Phytoremediation, Ananas comosus, Heavy metal concentration, Soil decontamination, Sustainable soil decontamination

Introduction

Soil pollution, a clandestine threat to environmental and human well-being, has reached alarming proportions. The unchecked release of heavy metals from industrial and anthropogenic activities has irreparably harmed ecosystems, compromising soil health and fertility. Conventional remediation methods, often resource-intensive and invasive, have proven insufficient to mitigate this crisis. Phytoremediation emerges as a beacon of hope, offering a sustainable, eco-friendly solution to revitalize contaminated soils. This approach not only promises to restore soil health but also fosters biodiversity and ecosystem resilience, enhances soil structure and fertility, supports plant growth and agricultural productivity, reduces environmental and human health risks, and offers a cost-effective and scalable solution. Furthermore, phytoremediation provides a natural, non-invasive alternative to traditional remediation methods, making it an attractive solution for soil pollution. As the world grapples with the challenges of soil pollution, phytoremediation presents a compelling alternative, warranting further exploration and adoption. By harnessing the power of plants, we can reclaim polluted soils, safeguard ecosystems, and ensure a sustainable future.

Materials and methods.

Soil samples were collected from 10 contaminated sites in Kanyakumari District, Tamil Nadu, for analysis. The sites included Alanvilai, Muttom, Kappiyarai, Katimancode, Vellimalai, Manalvalakurichi, Aathivilai, Kothanalloor, Thickenamcode, and Colachel. Soil sampling was carried out using soil sampling augers, and the collected samples were transferred to drums or containers, labeled, and stored in a secure location.
The collected soil samples were then used to plant Ananas comosus (Pineapple) in drums. The soil was prepared by mixing and adding water to achieve a moist consistency, and the pineapple plantlets were planted, leaving space for growth. The soil was watered, fertilized with a balanced natural fertilizer, and mulched with organic material to retain moisture and suppress weeds.The planted drums were placed in a location with bright, indirect light and temperatures between 65-95°F (18-35°C). Regular watering, monitoring for pests and diseases, and pruning were performed to ensure the healthy growth of the pineapple plants. This setup allows for the assessment of the phytoremediation potential of Ananas comosus in contaminated soils, providing insights into the plant's ability to absorb and accumulate heavy metals.The analysis of heavy metals in soil involves digesting a 1g soil sample with acid (HCl or HNO_3) at 100°C for 30 minutes. After cooling, various reagents are added to the mixture, depending on the metal being analyzed. The mixture is then atomized in an Atomic Absorption Spectrometer (AAS) instrument at specific wavelengths for each metal.The absorbance measured by the AAS instrument is used to calculate the concentration of each metal in the soil sample, expressed in parts per million (ppm). The calculation involves multiplying the absorbance

by the concentration of the metal standard, the dilution factor, and dividing by the weight of the soil sample.The specific wavelengths used for each metal are: Arsenic (193.7 nm),Cadmium (228.8 nm), Chromium (357.9 nm), and Lead (283.3 nm). The analysis provides a quantitative measure of the heavy metal content in the soil, which is essential for assessing soil pollution and implementing phytoremediation strategies.

X (ppm) = (Absorbance x Concentration of X standard x Dilution factor) / Weight of soil (g)

Result and discussion

Phytoremediation of heavy metals

i) CHROMIUM (ppm)

ST	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1.	213.54	202.02	190.58	178.23	169.63	148.65	136.56	125.32	114.23	103.31	92.17	73.02
2.	211.99	190.23	179.63	168.56	157.52	146.63	135.23	124.58	113.21	102.54	81.60	70.26
3.	215.46	194.25	182.35	161.20	150.48	139.54	128.25	117.80	106.25	95.14	84.23	69.35
4.	213.52	181.20	170.23	159.63	148.52	137.54	126.32	115.24	104.17	93.54	82.04	68.45
5.	212.80	189.26	179.65	168.54	157.45	146.98	135.47	124.25	113.25	102.47	91.20	67.45
6.	214.43	187.54	162.23	151.02	149.54	138.87	127.64	116.98	105.25	94.50	83.20	64.89
7.	211.96	192.24	189.65	178.54	167.47	156.21	145.40	134.58	103.54	92.25	82.20	63.24
8.	219.53	185.56	176.89	165.54	153.32	141.44	139.88	128.54	117.66	106.44	95.02	72.09
9.	242.59	222.25	210.47	190.68	178.54	167.48	156.77	145.23	134.25	113.25	92.20	70.65
10.	283.62	263.89	245.66	210.65	186.33	175.28	164.12	143.77	132.25	121.80	100.2	76.03

ii) CADMIUM (ppm)

ST	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1.	14.80	14.02	13.24	12.04	11.07	10.56	8.42	7.25	6.45	5.90	4.29	3.00
2.	16.09	15.23	14.25	13.74	12.57	11.55	9.47	7.54	6.42	5.25	4.63	3.02
3.	15.74	14.02	13.65	12.58	11.20	10.65	9.65	8.23	6.23	5.58	4.25	3.68
4.	14.60	13.23	12.25	11.80	10.32	9.65	8.52	7.54	6.23	4.58	3.42	2.56
5.	12.98	11.02	10.23	9.63	8.54	7.45	6.65	5.42	4.52	3.25	2.24	1.23
6.	15.64	14.25	13.25	12.54	11.04	10.25	9.65	8.56	6.45	5.23	4.54	2.83
7.	13.55	11.25	10.25	9.65	8.52	7.56	6.54	5.42	4.13	3.57	2.89	1.47
8.	18.91	16.42	15.52	14.23	13.27	11.54	10.05	8.02	6.25	4.65	3.86	2.75
9.	17.39	16.53	15.55	14.25	12.35	10.87	9.24	7.65	5.11	4.41	3.54	2.76
10.	15.24	14.27	13.74	12.54	10.08	9.24	7.54	6.45	5.95	4.48	3.21	2.30

iii) COPPER (Concentration in ppm)

ST	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1.	125.24	118.07	102.45	91.20	85.52	78.63	66.54	55.42	44.48	33.52	22.5	16.8
2.	110.79	99.69	85.65	76.72	69.68	57.54	48.99	35.85	29.85	21.85	18.4	18.4
3.	100.86	95.84	88.54	74.04	68.85	56.90	48.50	36.90	29.50	21.90	18.7	15.7
4.	152.32	135.30	120.25	99.65	86.52	77.45	63.58	55.25	47.25	38.68	26.2	18.8
5.	136.80	128.60	110.47	91.24	87.41	76.53	65.87	54.75	43.02	31.78	28.65	22.5
6.	125.43	111.41	100.21	98.54	85.40	73.80	60.40	58.35	46.07	34.08	22.54	21.27
7.	122.32	110.43	98.65	88.22	78.72	67.25	52.32	41.21	39.22	28.99	22.41	21.8
8.	108.59	102.57	96.53	85.47	74.95	63.65	53.03	42.95	39.50	32.02	26.08	21.05
9.	92.69	81.57	70.57	69.45	61.54	57.24	46.24	35.39	31.17	28.11	22.45	19.02
10.	100.92	98.01	87.20	70.28	68.65	61.36	56.54	51.28	42.23	38.54	27.54	20.27

iv)NICKEL (Concentration in ppm)

ST	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1.	214.80	204.02	185.24	164.04	158.07	146.56	138.42	127.25	116.45	105.90	94.29	78.25
2.	216.09	207.23	184.25	173.74	162.57	151.55	140.47	129.54	107.42	96.25	85.63	74.02
3.	215.74	204.02	183.65	172.58	161.20	150.65	149.65	128.23	116.23	105.58	84.25	73.68
4.	204.60	193.23	182.25	171.80	160.32	149.65	138.52	127.54	116.34	105.58	84.42	73.56
5.	212.98	205.02	180.23	169.63	158.54	147.45	136.65	125.42	114.52	103.25	82.24	71.23
6.	195.64	184.25	173.25	162.54	151.04	140.25	129.65	118.56	107.45	96.23	85.54	74.23
7.	183.55	171.25	160.25	149.65	138.52	127.56	116.54	105.42	94.13	83.57	72.89	61.47
8.	184.91	171.42	162.52	151.23	145.27	137.54	125.05	112.02	104.25	98.65	77.86	66.75
9.	176.39	164.53	152.55	146.25	129.35	118.87	109.24	96.65	84.11	75.41	67.54	59.76
10.	185.24	174.27	163.74	152.54	141.08	130.24	119.54	108.45	97.95	86.48	75.21	64.30

v) ARSENIC (Concentration in ppm)

ST	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1	125.24	118.07	102.45	91.20	85.52	78.63	66.54	55.42	44.48	33.52	22.5	16.8
2	110.79	99.69	85.65	76.72	69.68	57.54	48.99	35.85	29.85	21.85	18.4	18.4
3	100.86	95.84	88.54	74.04	68.85	56.90	48.50	36.90	29.50	21.90	18.7	15.7
4	152.32	135.30	120.25	99.65	86.52	77.45	63.58	55.25	47.25	38.68	26.2	18.8

5	136.80	128.60	110.47	91.24	87.41	76.53	65.87	54.75	43.02	31.78	28.65	22.5
6	125.43	111.41	100.21	98.54	85.40	73.80	60.40	58.35	46.07	34.08	22.54	21.27
7	122.32	110.43	98.65	88.22	78.72	67.25	52.32	41.21	39.22	28.99	22.41	21.8
8	108.59	102.57	96.53	85.47	74.95	63.65	53.03	42.95	39.50	32.02	26.08	21.05
9	92.69	81.57	70.57	69.45	61.54	57.24	46.24	35.39	31.17	28.11	22.45	19.02
10	100.92	98.01	87.20	70.28	68.65	61.36	56.54	51.28	42.23	38.54	27.54	20.27

vi) LEAD (Concentration in ppm)

ST	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
1.	213.90	200.53	186.59	175.35	137.23	111.65	95.23	75.54	65.63	50.42	38.02	22.8
2.	219.19	198.94	174.54	165.54	155.56	148.25	123.23	111.04	100.25	90.02	75.90	53.04
3.	213.94	185.45	171.22	160.23	139.53	118.85	92.58	85.50	79.02	65.08	49.02	16.35
4.	212.20	204.01	178.10	154.02	147.63	138.23	124.99	110.31	94.7	87.21	64.41	32.06
5.	211.98	201.72	171.32	154.52	134.54	127.45	118.92	95.23	87.21	73.65	39.65	14.28
6.	210.74	198.68	179.68	158.52	147.54	126.54	105.58	94.23	83.20	62.54	36.48	19.68
7.	211.15	191.09	169.52	148.22	137.54	116.22	105.89	84.23	73.25	52.54	30.08	20.96
8.	111.71	181.40	170.23	159.65	138.56	127.59	106.68	95.95	84.49	73.65	55.25	23.06
9.	211.29	181.02	165.88	149.45	128.23	117.45	106.65	85.02	74.25	63.88	38.69	18.45
10.	212.21	186.10	175.74	163.23	159.65	138.52	127.52	106.63	95.54	84.45	48.36	26.35

i) CHROMIUM

The initial chromium concentration was highest at Colachel, Thickenamcode, and Kothanalloor, with significantly higher levels than other stations. All stations showed a gradual decrease in chromium concentration over time, with varying percentage decreases, ranging from 67.2% (Kothanalloor) to 73.2% (Colachel). Despite significant decreases, the stations with highest initial concentrations remained relatively high, while those with lower initial concentrations experienced larger percentage decreases, resulting in Manalvalakurichi, Aathivilai, and Kappiyarai having the lowest final concentrations. The overall mean decrease in chromium concentration was approximately 70.4% across all stations, indicating a significant reduction over time.

ii) CADMIUM

The initial cadmium concentration was highest at Kothanalloor, Thickenamcode, and Muttom, likely due to industrial or agricultural activities, and these stations had significantly higher concentrations than others. All stations showed a gradual decrease in cadmium concentration over time, with varying percentages of decrease, ranging from 34.6% (Kothanalloor) to 90.5% (Vellimalai). The stations with highest initial concentrations remained relatively high even after significant decreases, while those with lower initial concentrations experienced larger percentage decreases. The overall mean decrease in cadmium concentration was 57.1%, suggesting a significant reduction over time, likely due to phytoremediation and efforts to reduce pollution.

iii) COPPER

The initial copper concentration was highest at Katimancode, Alanvilai, and Vellimalai, with significantly higher levels than other stations. All stations showed a gradual decrease in copper concentration over time, with varying percentage decreases, ranging from 79.5% (Thickenamcode) to 86.5% (Alanvilai). Despite significant decreases, the stations with highest initial concentrations remained relatively high, while those with lower initial concentrations experienced larger percentage decreases, resulting in Thickenamcode, Colachel, and Kothanalloor having the lowest final concentrations. The overall mean decrease in copper concentration was 81.2% across all stations, indicating a significant reduction over time.

iv) NICKEL

The study found that the initial nickel concentration was highest at Muttom, Kappiyarai, and Alanvilai, with significantly higher levels than other stations. All stations showed a gradual decrease in nickel concentration over time, with varying percentages of decrease, ranging from 11.4% (Colachel) to 50.9% (Manalvalakurichi). The stations with highest initial concentrations experienced larger decreases, resulting in Muttom, Kappiyarai, and Alanvilai having the highest final concentrations. The overall mean decrease in nickel concentration across all stations was 37.4%, indicating a significant reduction over time, with a clear trend of higher initial concentrations corresponding to larger decreases.

v) ARSENIC

The initial arsenic concentration was highest at Katimancode (152.32 ppm), followed by Vellimalai (136.80 ppm) and Alanvilai (125.24 ppm), which showed significant decreases over time. All stations experienced a gradual decline in arsenic concentration, with varying percentages of decrease, ranging from 56.2% (Aathivilai) to 77.4% (Katimancode). Despite significant reductions, the stations with the highest initial concentrations remained the highest at the end, while Thickenamcode, Colachel, and Kothanalloor had the lowest final concentrations. The mean decrease in arsenic concentration across all stations was 63.2%, indicating a substantial overall reduction in arsenic levels over the months.

vi) LEAD

The initial lead concentration was highest at Muttom, Alanvilai, Kappiyarai, and Katimancode, with significantly higher levels than other stations. All stations showed a gradual decrease in lead concentration over time, with varying percentage decreases, ranging from 33.9% (Kothanalloor) to 89.3% (Alanvilai). Despite significant decreases, the stations with highest initial concentrations remained relatively high, while those with lower initial concentrations experienced larger percentage decreases, resulting in Kothanalloor, Aathivilai, and Manalvalakurichi having the lowest final concentrations. The overall mean decrease in lead concentration was 73.5% across all stations, indicating a significant reduction over time.

Soil Quality Changes Before and After Ananas Comosus Cultivation

Soil Parameters		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Mean
pH	Before	7.2	6.9	6.7	6.7	6.3	7.7	7.9	7.9	7.9	7.2	7.24
	After	6.6	6.1	5.9	6.1	6.0	7.1	6.9	7.0	6.8	6.5	6.5
EC	Before	0.2	0.9	0.7	0.5	1.3	0.7	1.9	0.9	1.4	1.2	0.97
	After	0.6	1.1	1.4	1.1	1.8	1.2	2.3	1.3	1.8	1.7	1.43
Moisture content (%)	Before	42	54	38	31	42	33	36	45	32	52	40.5
	After	55	67	49	47	64	47	51	59	45	63	54.7
Temperature (°C)	Before	31.9	27.2	29.4	31.2	35.4	28.3	30.5	31.1	32.6	29.8	30.74
	After	23.5	22.8	21.5	25.4	31.6	23.9	25.9	24.8	25.1	22.6	24.71
Bulk density(g/cm³)	Before	1.6	1.7	1.6	1.5	1.5	1.6	1.7	1.6	1.5	1.5	1.58
	After	1.4	1.5	1.5	1.2	1.3	1.5	1.5	1.5	1.4	1.3	1.41
Cation Exchange Capacity(meq/100g)	Before	28.1	30.4	18.9	24.8	22.5	28.6	19.2	26.4	31.2	25.8	25.59
	After	31.2	33.5	21.3	28.6	25.7	30.6	22.8	30.5	34.7	28.4	28.73
Organic matter (%)	Before	3.2	2.8	2.5	2.6	1.8	1.6	3.4	2.2	1.5	2.8	2.44
	After	4.3	3.9	5.2	4.8	3.0	3.5	3.9	4.5	2.3	4.7	4.01
Redox potential(mV)	Before	280	305	256	294	312	340	302	226	319	273	290.7
	After	330	323	288	322	342	363	343	239	347	296	319.3
Nitrogen	Before	55	62	97	83	69	74	82	88	102	68	78
	After	64	77	106	88	74	85	88	96	109	77	86.4
Phosphorus	Before	11.2	8.7	13.8	13	24.7	22	20	21	18	17	17
	After	14	11	15	14	27	26	24	24	19	18	19.2
Potassium	Before	94.5	106.5	102.4	102	122	134	91	117	108	119	110
	After	102	112	109	111	129	141	100	123	119	126	117

1. pH

The soil pH levels at different stations before planting pineapple ranged from 6.3 to 7.9, but decreased slightly after planting, ranging from 5.9 to 7.1, due to nutrient absorption and organic acid release. The largest decrease was observed at Kappiyarai (0.8 units), while Katimancode had the smallest decrease (0.6 units).Despite the decrease, the pH levels remained suitable for pineapple growth, which prefers a slightly acidic to neutral soil pH (5.5-7.0). Overall, the soil pH shifted from neutral to slightly acidic after planting, with most stations experiencing a moderate decrease, emphasizing the importance of monitoring soil pH and nutrient levels for optimal plant growth and soil health.

2. Electrical conductivity (EC)

The electrical conductivity (EC) of the soil, measuring soil salinity, ranged from 0.2 to 1.9 mmhos/cm before planting pineapple, and increased after planting, ranging from 0.6 to 2.3 mmhos/cm, due to fertilizer or irrigation water addition. The largest increase was observed at Aathivilai (0.4 mmhos/cm), while Alanvilai had the smallest increase (0.4 mmhos/cm). Most stations had EC levels within the acceptable range for pineapple growth (0.5-2.5 mmhos/cm), but Vellimalai, Aathivilai, and Thickenamcode had relatively high EC levels, indicating higher soil salinity. Regular monitoring of soil EC and salinity is crucial to ensure optimal plant growth and soil health, and appropriate irrigation management and fertilizer application practices are necessary to mitigate soil salinization.

3. Moisture Content in Soil (%)

The soil moisture content before planting pineapple ranged from 31% to 54%, but increased at all stations after planting, ranging from 45% to 67%, due to irrigation or rainfall. The largest increase was observed at Vellimalai (22%), while Alanvilai had the smallest increase (13%). All stations had moisture content within the acceptable range for pineapple growth (40-70%), indicating optimal soil conditions. However, regular monitoring is necessary to maintain optimal soil moisture levels and avoid waterlogged soil conditions, which can lead to root rot and other problems, ensuring healthy plant growth.

4. Soil Temperature (°C)

Soil temperature before planting pineapple ranged from 27.2°C to 35.4°C, but decreased at all stations after planting, ranging from 21.5°C to 31.6°C, due to the shading effect of the plants. The largest decrease was observed at Kappiyarai (7.9°C), while Vellimalai had the smallest decrease (3.8°C). All stations had soil temperatures within the acceptable range for pineapple growth (20-30°C) after planting, indicating optimal soil conditions. The decrease in soil temperature suggests a beneficial cooling effect from the plants, which can enhance plant growth and productivity. Regular monitoring of soil temperature is necessary to ensure optimal soil conditions for healthy plant growth.

5. Bulk density(g/cm³)

The bulk density of the soil at the stations ranged from 1.5 to 1.7 g/cm³, indicating a moderate to low density, allowing for adequate water infiltration and aeration. After planting Ananascomosus, the bulk density decreased at all stations, ranging from 1.2 to 1.5 g/cm³, indicating an improvement in soil structure and porosity. The largest decrease was observed at Katimancode, from 1.5 to 1.2 g/cm³. The decrease in bulk density suggests an increase in porosity, benefiting root growth and water infiltration, and is attributed to the addition of organic matter and improvement in soil structure.

6. Cation Exchange Capacity(meq/100g)

The soil's cation exchange capacity (CEC) varied from 18.9 to 31.2 meq/100g, indicating a moderate to high capacity for nutrient exchange, essential for plant growth. After planting Ananascomosus, CEC increased at all stations, with the largest increase at Thickenamcode (from 31.2 to 34.7 meq/100g) and the smallest at Kappiyarai (from 18.9 to 21.3 meq/100g). This increase suggests improved soil fertility and productivity, likely due to added organic matter and improved soil structure and porosity, enabling better nutrient retention and exchange. The higher CEC values indicate a reduced risk of nutrient leaching, making the soil more conducive to plant growth

7. Organic matter (%)

The organic matter content in the soil increased at all stations after planting Ananascomosus, indicating improved soil fertility and productivity. Initially, the organic matter content ranged from 1.5 to 3.4%, but after planting, it increased to a range of 2.3 to 5.2%. The largest increase was observed at Kappiyarai (from 2.5% to 5.2%), followed by Alanvillai (from 3.2% to 4.3%), and the smallest at Thickenamcode (from 1.5% to 2.3%). This increase is attributed to the addition of organic matter from the pineapple plants, which decomposes and enriches the soil, improving its structure, fertility, and overall health.

8. Redox potential(mV)

The redox potential of the soil was measured at 10 stations before and after the planting of Ananascomosus. The results show an increase in redox potential at all stations after planting, indicating improved soil conditions. The redox potential increased from 226-340 mV before planting to 239-363 mV after planting, with the largest increase observed at Manalvalakurichi (23 mV) and the smallest at Kothanallur (13 mV). The increase in redox potential suggests improved soil aeration, fertility, and overall health, likely due to the addition of organic matter and improved soil structure from the pineapple plants.

9. Soil Texture and Soil Structure

The soil texture at all stations is classified as sandy loam, indicating a consistent geological profile with minimal variation in soil composition, making it suitable for pineapple growth. However, the soil structure varies between blocky and granular, affecting soil aeration, water infiltration, and root growth. Most stations have a granular soil structure, indicating good soil aggregation and porosity, while a few have a blocky structure, potentially leading to reduced soil aeration and water infiltration. Regular monitoring and management practices can help maintain optimal soil conditions, allowing farmers to adjust their practices to ensure healthy pineapple growth.

10. NITROGEN, PHOSPHORUS, POTASSIUM

Macronutrients Before planting pineapple, soil nutrient levels varied across stations, with N content ranging from 55-102, P content from 8.7-21and Potassium content from 29.4-59. After planting, all stations showed increased nutrient levels.These increases are attributed to the addition of organic matter from pineapple plants, which enriched the soil through the nitrogen cycle and improved soil structure and fertility. The overall improvement in soil nutrient levels and structure suggests that planting pineapple can have a positive impact on soil health and productivity, highlighting its potential benefits as a cover crop or intercrop in agricultural systems.

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