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E-waste Leachate Contamination: Assessment of Trace Metal Pollution in Drinking Water, Soil and Agricultural Systems

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ABSTRACT

Introduction: Improper management of electronic waste (e-waste) is an escalating global issue that poses severe risks to environmental quality and public health. This study systematically evaluated the impact of e-waste leachate on trace metal pollution in drinking water, soil, and agricultural systems. **Methodology:** Discarded television circuit boards were processed and used as a contamination source in controlled laboratory experiments simulating both waterborne and soil-based e-waste exposure. In the water contamination trials, 5 kg of e-waste fragments were leached in 25 liters of bore well water over three months, with monthly analysis of lead (Pb), copper (Cu), and chromium (Cr) concentrations using Atomic Absorption Spectroscopy (AAS) and Atomic Fluorescence Spectroscopy (AFS). Parallel experiments exposed garden soil and tomato plants to both solid e-waste and its leachate. Metal concentrations were quantified in all environmental matrices, and plant growth was monitored over six months. **Results:** Results revealed a significant increase in chromium and lead levels in both water and soil following e-waste exposure, with maximum observed concentrations of 1.625 ppm Cr and 1.029 ppm Pb in water, and up to 6.996 ppm Pb and 3.840 ppm Cr in soil directly mixed with e-waste. Plants grown in contaminated conditions showed reduced growth rates, with the lowest heights (9.4 cm) observed in those exposed to leachate-contaminated water. The findings underscore the high mobility of toxic metals from e-waste and their detrimental effects on plant health. **Conclusion:** In conclusion, this work demonstrates that improper e-waste disposal leads to significant trace metal contamination in critical environmental resources, posing risks to both food safety and ecosystem function. Effective e-waste management policies prioritizing recycling and safe disposal are urgently needed to mitigate such hazards.

Keywords: e-waste; trace metals; leachate; heavy metal contamination; drinking water; soil pollution;

1. INTRODUCTION

Electrical and electronic equipment has become an essential part of modern life, yet its disposal has evolved into a major environmental challenge due to the rapid increase in waste electrical

and electronic equipment (e-waste) generation worldwide. E-waste contains a complex mixture of toxic, precious, and base metals, and its improper disposal can pose significant risks to both human health and environmental quality due to the release of hazardous substances [1,2]. The toxicity of these metals depends greatly on the environmental conditions in which they are released and their bioavailability.

Global production of e-waste is accelerating, with 53.6 million metric tons generated in 2019 and estimates projecting an increase to over 74.7 million metric tons by 2030. Common sources include discarded cell phone screens, computer components, and industrial machinery, all of which contain high concentrations of hazardous chemicals and heavy metals that threaten ecosystems and human populations [3,4]. E-waste contaminants are capable of leaching into soil and water, entering the food chain and ultimately affecting human health through oral ingestion, dermal absorption, or crop uptake [5].

Numerous studies have reported elevated levels of toxic metals in soils and waters affected by e-waste, with the degree of contamination influenced by disposal methods and exposure conditions [6]. Recent research has also shown that e-waste leachates have direct toxic effects on aquatic organisms and plants, further illustrating the urgent need for effective waste management strategies. Despite these risks, the proportion of e-waste that undergoes proper disposal and recycling remains disappointingly low worldwide [7].

The present study aims to assess the impact of e-waste disposal on trace metal contamination in drinking water and soil, utilizing various analytical methods to evaluate lead, copper, and chromium levels. By systematically investigating how these approaches influence the results, this work seeks to provide a clearer understanding of the pathways and risks associated with e-waste pollution, thereby informing policies and practices for better environmental protection.

NEED FOR THE STUDY

The rapid increase in electronic waste (e-waste) generation has emerged as a significant environmental issue, particularly in urban areas lacking robust recycling infrastructure. Improper disposal practices lead to leaching of toxic heavy metals such as lead, copper, and chromium from discarded electronic components into water, soil, and agricultural systems. These contaminants pose major threats to environmental health, agricultural productivity, and human well-being by entering food chains through crop uptake and groundwater

contamination. Despite growing acknowledgment of these dangers, limited systematic data are available on the levels and pathways of trace metal pollution originating from e-waste, especially in developing regions. This gap hinders the formulation of effective intervention strategies and regulatory policies for e-waste management. Therefore, a comprehensive investigation into the movement and accumulation of these hazardous metals in different environmental media is essential to assess their impact and guide protective measures for public health and ecological stability.

AIM OF THE STUDY

The aim of this study is to assess the impact of e-waste disposal on trace metal contamination in drinking water, soil, and crops. Evaluate the levels of lead, copper, and chromium released from e-waste into environmental systems. Provide evidence to inform policies for safer e-waste management and environmental protection.

2. METHODOLOGY

The experimental setup involved preparing E-waste samples from discarded television circuit boards, which were collected from a local junkyard and mechanically broken into pieces smaller than 2 cm^2. These fragments provided standardized E-waste material for subsequent leaching and contamination studies.

2.1 E-Waste Leaching in Water

For the water contamination experiments, 5 kg of the prepared E-waste fragments were added to 25 L of bore well water sourced from a depth of 150 ft in K.K. Nagar, Chennai, resulting in a material concentration of 20%. The mixture was kept in a single container and stirred periodically throughout the three-month leaching study (October–December 2023). Each month, 200 mL of leachate was removed and filtered through a 40 µm Whatman filter, generating a series of leachate samples (ELW1 to ELW6) at monthly intervals; the withdrawn volume was replenished with fresh bore well water to maintain a constant volume.

2.2 E-Waste Leaching in Soil

The soil contamination study utilized four container setups:

- Container 1: 10 kg of garden soil (GS), watered every two days with 200 mL bore well water (BW).
- Container 2: 2 kg E-waste mixed with 10 kg GS, watered similarly, providing sample 2ELS1 after one month.
- Container 3: 2 kg E-waste mixed with 10 kg GS, watered as above; subsamples (3ELS1 to 3ELS6) were collected monthly from October to March, dried, and sieved for analysis.
- Container 4: 10 kg GS; beginning after one month, soil was irrigated every two days with 200 mL of sequentially collected E-waste leachate (ELW1 to ELW5), generating


samples (4ELWS1 to 4ELWS5) each month.

Fig. 1 e-waste and container containing e-waste in bore well

2.3 Plant Contamination and Growth Analysis

Tomato seeds (20 g per container) were sown as follows:

- Containers 1 and 2: seeds sown at the start (October 2023), plants grown for six months, yielding samples 1GSP and 2ELSP.
- Containers 3 and 4: seeds sown after one month (November 2023), plants grown for up to six months, yielding samples 3ELSP and 4ELWSP.

The growth of tomato plants was monitored, and at the end of six months (February 2024), all plants were harvested and dried in shade. Water, soil, and plant samples were analyzed for lead, copper, and chromium content using atomic absorption spectroscopy.

3. CHARACTERIZATION TECHNIQUES

Experimental analyses of the samples were performed at Kiyo R&D Center and Laboratory, Chennai, India, using gas chromatography (GC) and atomic fluorescence spectroscopy (AFS). Gas chromatography measurements utilized a modern GC system with helium or nitrogen as the carrier gas, enabling the sensitive separation of volatile and semi-volatile organic compounds; model specifications closely followed standard GC-MS protocols as described for their in-house equipment. Elemental concentrations were determined by atomic fluorescence spectroscopy (AFS), which incorporated a nebulizer-burner system and monochromator for emission detection, applying industry-standard instrumentation suitable for trace-level analysis of metals.

4. RESULTS AND DISCUSSION

4.1 Water Contamination by E-Waste

Electrical and electronic equipment synthesized and developed using high-functional nanoparticles has become an essential part of modern life [8,9]. The leachate samples derived from water contaminated with e-waste were analyzed for the presence of Lead, Copper, and Chromium. Concentrations of these heavy metals varied across different samples (ELW 1–ELW 6) and the background water (BW), as summarized in Table 1.

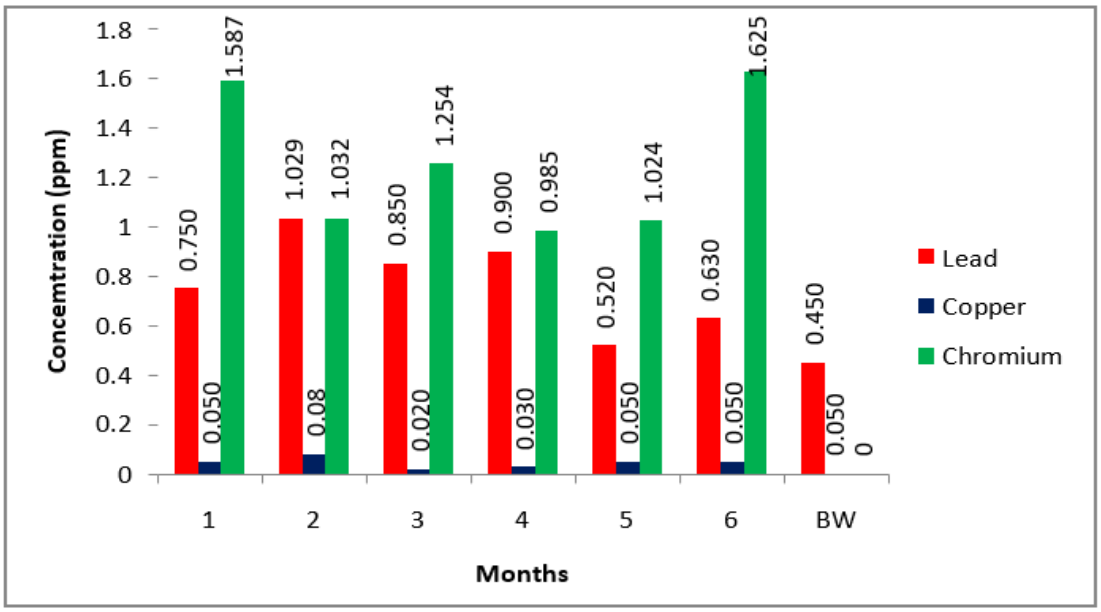

Fig. 2 Presence of Heavy Metals in Leachate

Table 1: Presence of Heavy Metals in water contaminated by E- waste

SI. No.	Presence of heavy metals (ppm)			
	Sample Code	Lead	Copper	Chromium
1	ELW 1	0.750	0.050	1.587
2	ELW 2	1.029	0.08	1.032
3	ELW 3	0.850	0.02	1.254
4	ELW4	0.900	0.030	0.985
5	ELW5	0.520	0.05	1.024
6	ELW6	0.630	0.050	1.625
7	BW	0.450	0.050	Nil

Notably, the background water (BW) contained 0.450 ppm of Lead and trace levels of Copper, but no detectable Chromium. The contamination from e-waste markedly increased Chromium concentrations, with the highest value observed in ELW6 (1.625 ppm). Lead was consistently present in all leachates, peaking at 1.029 ppm in ELW2. Copper levels remained comparatively low throughout. The extent of leaching varied with the size of the e-waste particles, with smaller particles facilitating greater leaching of Lead and Chromium. The data indicate that Chromium leaches more strongly than Lead from e-waste into water, while Copper is less pronounced [5][10].

4.2 Soil Contamination by E-Waste and Leachate

Heavy metal concentrations were also measured in soils directly contaminated with e-waste and soils contaminated via leachate, with results provided in Tables 2 and 3.

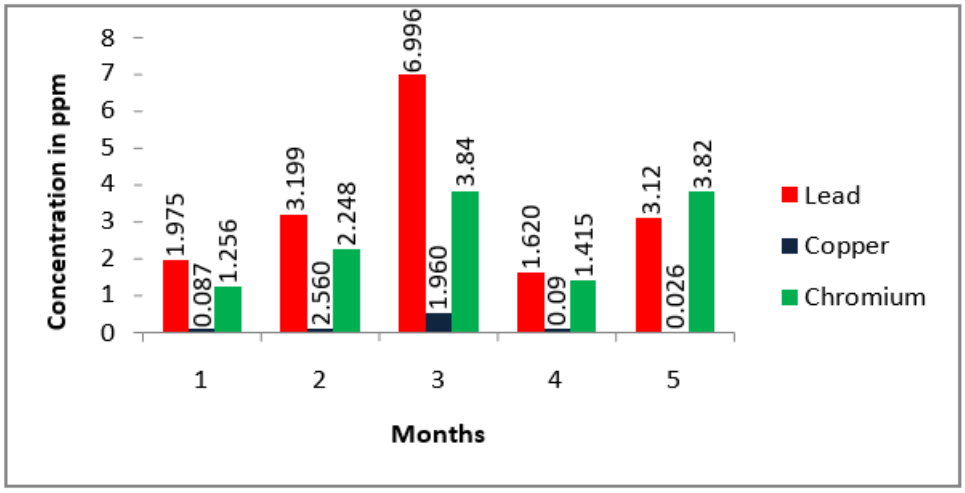

Fig. 3 Presence of Lead in the soil samples 3ELS

Table 2: Presence of Heavy Metals in soil contaminated by E- waste

SI. No.	Presence of heavy metals (ppm)			
	Sample Code	Lead	Copper	Chromium
1	3ELS1	1.975	0.087	1.256
2	3ELS2	3.199	0.101	2.248
3	3ELS3	6.996	0.521	3.840
4	3ELS4	1.620	0.090	1.415
5	3ELS5	3.120	0.026	3.820
6	1GS	0.840	0.120	2.401

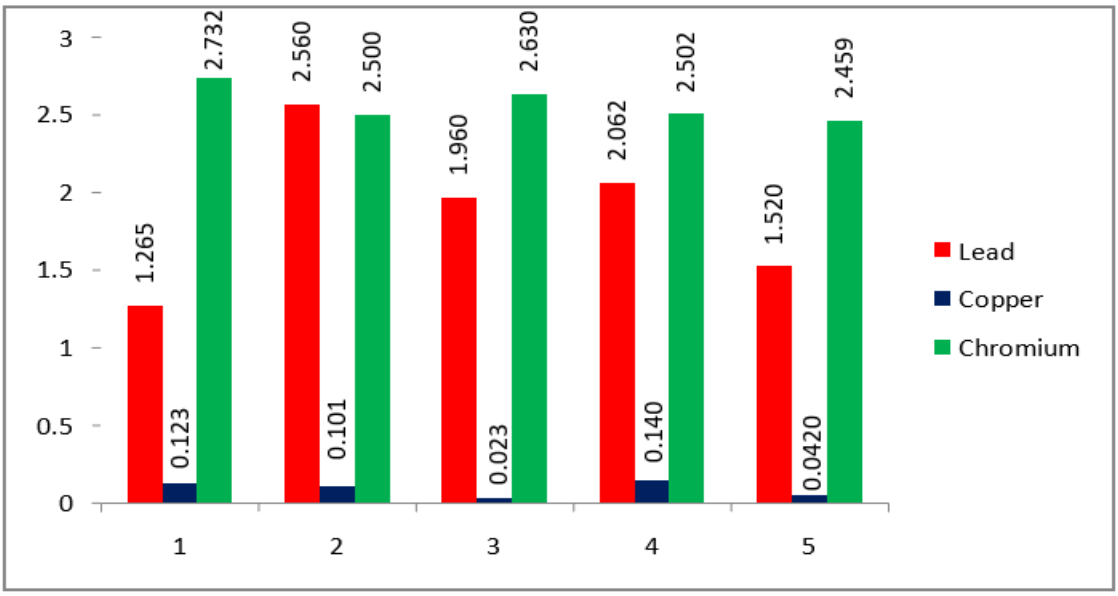

Fig. 4 Presence of Heavy Metals in soil samples 4ELWS

Table 3: Presence of Heavy Metals in Soil Contaminated by Leachate

SI. No.	Presence of heavy metals (ppm)			
	Sample Code	Lead	Copper	Chromium
1	4ELWS1	1.265	0.123	2.732
2	4ELWS2	2.560	0.101	2.500
3	4ELWS3	1.960	0.023	2.630
4	4ELWS4	2.062	0.140	2.502
5	4ELWS5	1.520	0.042	2.459

Soils contaminated directly by e-waste exhibited the highest concentrations of heavy metals, especially Lead (up to 6.996 ppm in 3ELS3) and Chromium (up to 3.840 ppm in 3ELS3). In contrast, soils contaminated by leachate showed a narrower range of Lead and Chromium concentrations, suggesting less intense contamination compared to direct contact with solid e-waste [11,12].

4.3 Impact on Plant Growth

A six-month study assessed the impact of e-waste contamination on the growth of tomato plants. Plants grown in uncontaminated soil (1GSP) attained a maximum height of 55.8 cm. Those grown in soils mixed with e-waste (2ELSP) reached 42.3 cm, while plants in soils pre-contaminated by e-waste over a month (3ELSP) grew to 25.4 cm. The most affected group comprised plants exposed to water contaminated by e-waste leachate (4EWLSP), which reached only 9.4 cm in height.

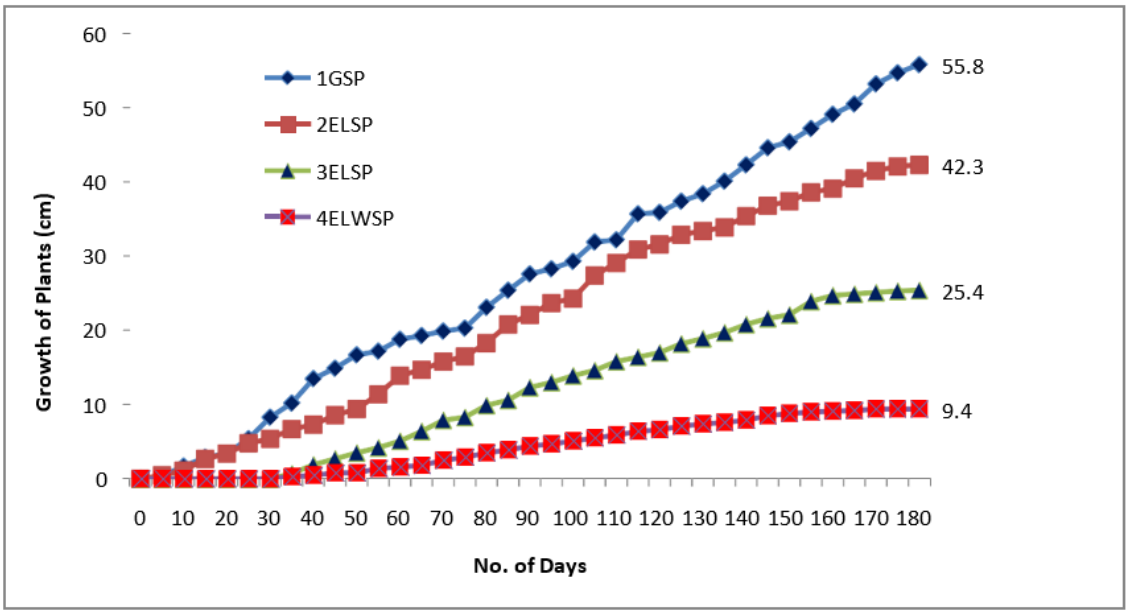

Fig. 5 Growth rate of the plant during the period of study

Table 4: Growth rate of the plants during the period of study

SI. No.	No of days	1GSP cm	2ESP cm	3ESP cm	4EWSP cm
1	0	0	0	0	0
2	5	0.4	00.5	0	0
3	10	1.7	1.1	0	0
4	15	2.9	2.7	0	0
5	20	3.4	3.4	0	0
6	25	5.4	4.8	0	0
7	30	8.3	5.4	0	0
8	35	10.2	6.7	0.7	0.3
9	40	13.5	7.3	1.9	0.5
10	45	14.9	8.6	2.7	0.8
11	60	16.7	9.4	3.5	0.8
12	55	17.2	11.4	4.2	1.4
13	50	18.8	13.9	5.1	1.6
14	65	19.3	14.7	6.4	1.8

SI. No.	No of days	1GSP cm	2ESP cm	3ESP cm	4EWSP cm
15	70	19.9	15.8	7.9	2.5
16	75	20.3	16.5	8.3	2.9
17	80	23.1	18.3	9.9	3.5
18	85	25.4	20.8	10.6	3.9
19	90	27.6	22.1	12.3	4.4
20	95	28.3	23.7	13	4.7
21	100	29.3	24.3	13.9	5.1
22	105	31.9	27.4	14.6	5.5
23	110	32.2	29.1	15.8	5.9
24	115	35.7	30.9	16.4	6.4
25	120	35.9	31.6	17	6.6
26	125	37.4	32.9	18.2	7.1
27	130	38.4	33.4	18.9	7.4
28	135	40.1	33.9	19.7	7.6
29	140	42.3	35.4	20.8	7.9
30	145	44.6	36.8	21.6	8.5
31	150	45.4	37.4	22.1	8.8
32	155	47.2	38.6	23.9	9.0
33	160	49.1	39.1	24.7	9.1
34	165	50.5	40.5	24.9	9.2
35	170	53.2	41.5	25.1	9.4
36	175	54.7	42.1	25.3	9.4
37	180	55.8	42.3	25.4	9.4

Table 5. Final Heights of Tomato Plants After Six Months

Condition	Final Height (cm)
Natural soil (1GSP)	55.8
Soil + e-waste	42.3
Pre-contaminated	25.4
Water leachate	9.4

The data demonstrate substantial inhibition of plant growth due to e-waste contamination, with water carrying leachate exerting the most severe effects. Reduction in growth correlated with increasing concentrations of Lead and Chromium, indicating that assimilation of these toxic metals adversely affects plant health and yield. This is also observed and reported in a review on toxic effects of chromium on legume plants and legume-rhizobium symbiosis [13].

4.4 Study of leachate using gas chromatography

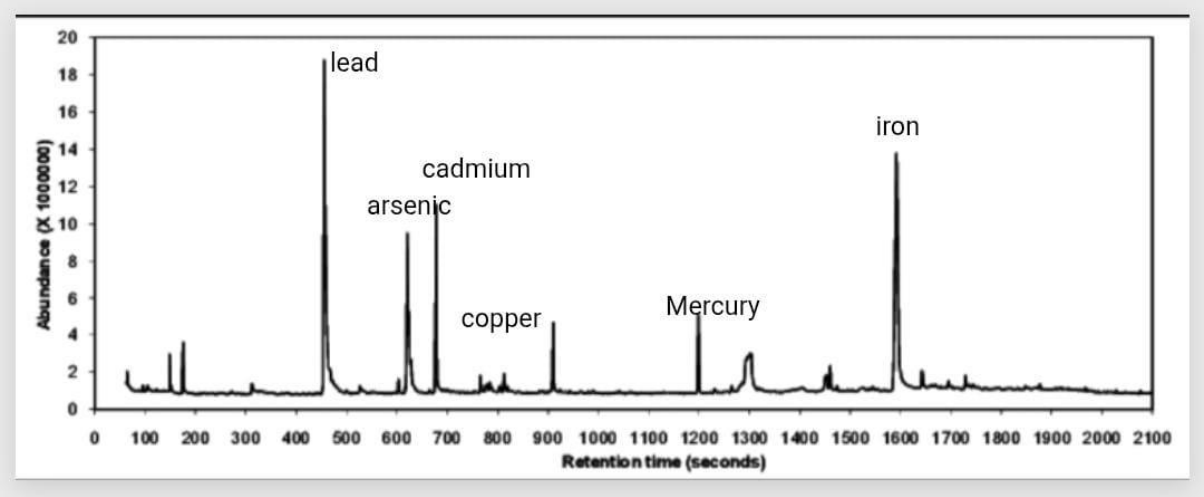

Fig. 6 Chromatogram showing the separation and detection of heavy metals

Figure 6 shows the chromatogram of the sample analyzed, illustrating the retention times and relative abundances of detected heavy metals. Distinct peaks corresponding to lead, arsenic, cadmium, copper, mercury, and iron were clearly resolved, allowing for the simultaneous quantification of these toxic elements. Lead exhibits the most prominent peak with the highest abundance, appearing around 450 seconds, indicating a significant concentration within the tested sample. Arsenic and cadmium produce adjacent peaks at approximately 600–700 seconds, both with moderate abundance. Copper appears as a distinct, smaller peak around 900 seconds, while mercury is identified near 1250 seconds, also at moderate intensity. Iron emerges later, at about 1550 seconds, and displays a substantial peak, denoting a high relative abundance. The separated peaks demonstrate the effectiveness of the method in resolving multiple heavy metals from a complex sample matrix. The varying intensities and retention times suggest differences in analyte concentrations and affinities for the chromatographic medium. These results enable quantitative and qualitative analysis of heavy metal contamination, crucial for environmental, biological, or food safety assessments.

4.5 Study of leachate using atomic fluorescence spectroscopy

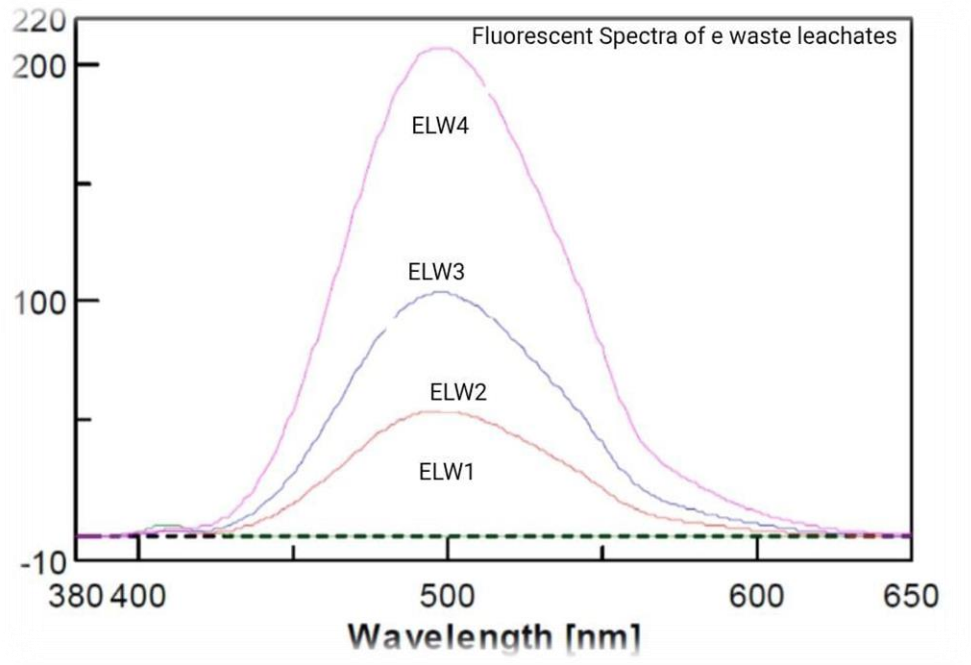

Fig. 7 Fluorescence Emission Spectra of E-Waste Leachate Samples (ELW1–ELW4)

The fluorescent spectra of e-waste leachates (ELW1 to ELW4) demonstrate a significant increase in fluorescence intensity with higher sample numbers, all showing a prominent emission peak at approximately 500 nm. ELW4 exhibits the highest fluorescence, followed sequentially by ELW3, ELW2, and ELW1, suggesting a progressive accumulation of fluorescent compounds or metals as the leachate number increases. The clear separation and enhancement of the spectral peaks imply varying concentrations or compositions of fluorescent species within each leachate, likely reflecting differences in leachate preparation, treatment, or origin. This spectral pattern highlights the sensitivity of fluorescence techniques in monitoring and comparing the composition and properties of e-waste-derived leachates, potentially providing insights into contamination levels and the efficiency of extraction processes.

4.6 Environmental and Health Implications

The results clearly show that improper disposal of e-waste leads to leaching of toxic heavy metals into water bodies and soil, thereby contaminating environmental resources. Such contamination not only hampers plant growth but may also pose significant health risks through metal uptake in edible plants. Lead and Chromium, in particular, are highlighted as key hazards due to their propensity to leach and be assimilated by crops [5,7].

5. CONCLUSION

Improper disposal of e-waste causes significant environmental contamination, as evidenced by the elevated concentrations of toxic trace metals, particularly Lead and Chromium**,** found in water, soil, and tomato plants exposed to e-waste and associated leachates. The findings highlight that direct soil contact with solid e-waste results in the highest metal accumulation, while waterborne leachate also causes marked pollution, with chromium consistently leaching at the greatest levels. The adverse effects on plant growth, especially a drastic reduction in tomato plant height under contaminated conditions, underscore the threat posed to both agricultural productivity and food safety.

The study demonstrates the urgent need for robust e-waste management strategies to mitigate environmental and health risks. Effective policies should prioritize segregated collection, recycling, and safe disposal to prevent hazardous metal mobilization from e-waste, especially in rapidly urbanizing regions. Further research is warranted to refine analytical methods, elucidate pathways of metal uptake in crops, and assess long-term ecosystem impacts. Actionable interventions can help safeguard drinking water, protect soil quality, and minimize plant and human exposure to persistent contaminants, ultimately ensuring healthier environments for present and future generations.

Author contributions

Giruba M- Formal analysis, Investigation, Methodology, Data Curation, Writing - Original Draft, Project administration. **Karthikeyan E**- Writing – review & editing, Visualization, Validation, **Vasanthi V**- Writing – review & editing, Visualization, Validation, **D. Hema G-** Writing – review & editing, Visualization, Validation, Methodology

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Data Availability:

Data will be made available upon request made to the corresponding author.

Declaration of competing interest:

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

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