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Environmental Impact of E-Waste on Biotic and Abiotic Parameters

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ABSTRACT

The exponential increase in electronic waste (e-waste) caused by rapid technological change is now a global environmental issue, particularly in urban informal economies, as lamented in Seelampur, Delhi. This study evaluated the environmental impacts of e-waste on biotic and abiotic parameters, specifically by assessing heavy metal contamination in soil, groundwater, plants, microorganisms, and smaller fauna. Employing mixed-method methodologies, the research employed a stratified random sampling technique throughout six sites, followed by the collection and analysis of soil and groundwater samples utilizing inductively coupled plasma–mass spectrometry (ICP-MS), as well as assessments of microbial diversity, plant uptake, and accumulation in animals. In terms of quantitative findings, lead, cadmium, mercury, and chromium concentrations were very high in relation to the World Health Organization (WHO) and national allowed limits and generally exceeded the WHO and permissible limits, with statistically significant differences in spatial exposures. Biological assessments based on soil microbial diversity revealed a diminishment in the microbial range, quantifiable signs of vegetal stress, and quantifiable bioaccumulation in invertebrates. Occupational health records also indicated high levels of harmful exposures to e-waste workers. The study concluded that informal e-waste recycling practices are correlated with quantifiable negative effects on ecosystem functions and human health indicators, and that there is an urgent need to provide good environmental practices through environmental regulations, raise awareness of the issue, and sustain approaches to mitigate long-term environmental degradation and negative public health outcomes.

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INTRODUCTION

Electronic waste (e-waste) is a byproduct of broken or obsolete electrical devices and electronics, such as televisions, laptops, mobile phones, washing machines, fans, and air conditioners. The enormous demand for electronic devices in human civilization has led to the worldwide generation of e-waste, which is a major concern (Castro & Bassin 2022). The worldwide increase in e-waste creation is mostly attributable to the exponential expansion of computer and communication devices, among other electrical consumables. The adaptability of electronic equipment, the fast expansion of technology and current breakthroughs, the rapidly dropping flow of costs of electronic gadgets, and the quick evolution of the information and communication sectors are further factors contributing to the vast output of e-waste (Lee et al. 2024).

Global electronic waste (e-waste) generation is rapidly increasing because of advancements in information and communication technology, artificial intelligence, and the widespread adoption of electronic devices, semiconductors, electric vehicles, and energy storage systems (Goh et al. 2022). The improper disposal of e-waste endangers ecosystems and human health, primarily because of hazardous components, including heavy metals and brominated flame retardants (Chen et al. 2021). Employing eco-friendly recycling technologies is important because inadequate recycling contributes to environmental pollution. It is particularly important to divert hazardous substances from recycling processes and ensure

their safe disposal in secure repositories (Li & Achal 2020).

The technology sector is the largest industrial sector in terms of size and growth rate. The very existence of contemporary luxury is dependent on human beings' heavy use of technology (Arya & Kumar 2020). Consequently, the demand for and use of such equipment have grown worldwide (Hijazi et al. 2021). A substantial volume of electrical waste has been generated because of the proliferation of new devices. According to a recent poll, approximately five billion out of seven billion people worldwide can meet their most fundamental needs (Rautela et al. 2021). Additionally, mobile phones have become an absolute necessity, with over six billion people using them. This poses documented risks to ecosystems and human health. Fati et al. (2022) highlighted the significant consequences of the electronics industry's enormous amount of e-waste (Ghulam & Abushammala 2023).

Consequently, e-waste comprises expensive and durable materials. According to Kumar et al. (2024), when people refer to "electronic trash," they usually mean anything that requires power or energy to function. In technical terms, electrical and electronic equipment is referred to as e-waste. Considering that e-waste contains a thousand or more components, its composition is very complicated and challenging (Ahirwar & Tripathi 2021).

Another approach to classifying these compounds is to determine whether they are hazardous. Although we have demonstrated that many factors may contribute to e-waste, landfills house the vast majority of this material. The first of three key reasons why e-waste is rapidly becoming a serious health risk is that there is very little known about how to properly manage and handle this type of garbage (Silva et al. 2023). Indirectly or directly, trash of all types has a major impact on people's mental and physical well-being (Parvez et al. 2021). Indirectly or directly, trash of all types has a major impact on people's mental and physical well-being (Parvez et al. 2021). Finally, the number of laws controlling the recycling of electronic trash has decreased due to the rapid development of automation. Human behavior is a major contributor to electronic waste (Abalansa et al. 2021).

The rapid increase in electronic waste (e-waste) generation is a direct result of the rapid evolution of technology and rising customer demand. E-waste refers to discarded electronic products, such as old cell phones, laptops, TVs, and batteries (Shahabuddin et al. 2023). The rapid replacement of technology owing to its short lifespan results in significant amounts of waste. E-waste, especially in poor nations, is not officially recycled and ends up in landfills or the informal recycling industry. Owing to the presence of hazardous components, including lead, mercury, cadmium, and brominated flame retardants, in electronic trash, their improper disposal contributes to soil, water, and air contamination through hazardous substances such as lead, mercury, and cadmium (Boubellouta & Kusch-Brandt 2020). All parts of the ecosystem, living and non-living, must be included in the ongoing effort to understand the effects of e-waste on the planet (Ádám et al. 2021).

Soil and water are examples of abiotic environmental components significantly affected by e-waste. The chemicals and heavy metals in discarded electronics seep into the groundwater when dumped in a landfill or left unattended. Yu et al. (2023) demonstrated the potential to destroy soil fertility, structure, and pH, rendering the area unfit for farming and plant life. Heavy rains and the flow of groundwater may also transport pollutants to other bodies of water, even far from the site of pollution. Consequently, subterranean aquifers, rivers, and lakes may also be contaminated (Beula & Sureshkumar 2021). Water quality is compromised, making it unsafe for humans and animals to drink. Arsenic and lead are toxic substances that degrade water and soil quality, some of these elements may persist in the natural environment for decades, posing a threat to aquatic ecosystems and human and environmental health (Mor et al. 2021). In several developing nations, unregulated e-waste recycling through open burning leads to the leakage of hazardous materials, including dioxins and furans, which pollute the local air and soil (Rasheed et al. 2022). This type of emission adversely affects air quality and contributes to global warming. Over time, emissions, such as greenhouse gases and fine particles in the air, impact health and shift climatic divergence (Awasthi et al. 2022). Air pollution from e-waste management activities in one area not only affects the air quality in that area but also contributes to global warming, climate change, and weather systems (Singh 2025).

E-waste exposure drastically impacts the biotic environment, which comprises plants, animals, and microorganisms. Toxic elements that plants absorb from contaminated soil and water can be transferred into the food chain, accumulating in herbivores and, ultimately, in humans (Thakur & Kumar 2022). Animals that consume plants or drink contaminated water experience neurological harm, organ failure, or reproductive harm (Mishra 2024). Chemical contaminants can affect microbial communities in the soil, which are key components of nutrient cycling and decomposition, thereby impacting soil health and productivity. Biodiversity loss from habitat degradation due to e-waste pollution is an additional pertinent issue that threatens ecosystem stability (Rawat 2020).

As the threat to living and non-living constituents of the environment continues to increase, it is vital to create and

implement sustainability management practices that will lead to systematic development (Ansari et al. 2022). This comes in the form of undertaking e-waste recycling through formal waste management sectors that utilize safe and standardized technologies (Heet al. 2024). Appealing to the government to implement stricter regulations and restrictions related to disposal practices also raises the bar for sustainability (Jain et al. 2023). Manufacturers are then targeted to adopt eco-design principles, which emphasize enabling the repair and reuse or recycling of electronic goods (Andeobu et al. 2023). Thus, combined with the implications of environmental education and government intervention, societies can lessen the harmful effects associated with e-waste and prevent detrimental impacts on living and the physical elements of the environment (Liu et al. 2023).

Although earlier studies focused on e-waste contamination worldwide and in some regions of India, most reported on a single environmental medium (e.g., soil only) or concentrated on occupational health measures only. There has been limited research on Seelampur that incorporates several environmental compartments, such as soil, groundwater, microbial diversity, plants, and invertebrates that are networked to the same spatially distinct framework. This study fills this gap by adopting a stratified random sampling scheme at six high-recycling-intensity sites to produce simultaneous abiotic and biotic data. By directly correlating contamination gradients with ecological stress indicators, the observations provide a new, multi-compartmental rendering of e-waste effects at the largest informal recycling center in India.

REVIEW OF LITERATURE

Toxic Leachates and Atmospheric Emissions from E-Waste

Chakraborty et al. (2022) identified many types of electronic waste, including plastics, glass, PCBs, cement, ceramics, rubber, and various precious metals, including copper, silver, gold, and platinum. They also listed important pollutants in this category, such as ferrous and non-ferrous metals. Arsenic, cadmium, chromium, mercury, and lead are toxic components that leak into the environment from e-waste. Adenuga et al. (2022) discarded that electronic devices produce e-waste. Over the last ten years, there has been a dramatic increase in the production of electronic trash. Electronic waste is increasing at a rate of over 2 Mt annually on a global scale. Approximately 74 million metric tons of electronic trash will be generated in 2030 (Igbo et al. 2022). Landfilling e-waste often leads to soil, surface, and subsurface water pollution. This contamination may impact plant development and cause toxicity in both surface and underground water sources. Lin et al. (2022) study showed that the released pollutants had a significant impact on local food products, particularly vegetables, rice, fish, and shellfish, as well as cattle, which were found to be highly contaminated with persistent organic pollutants (POPs).

Ecotoxicological and Health Consequences of E-waste Exposure

Eckhardt (2024) found that informal e-waste workers in low- and middle-income countries experience hormonally altered, respiratory, renal, cardiovascular, musculoskeletal, and skin health problems. Injuries and skin conditions were common among informal e-waste workers, with injury estimates reaching up to 89% of workers and 100% for skin conditions. Parvez et al. (2024) analyzed soil and dust samples from e-waste sites in Bangladesh and found significant amounts of the trace elements lead (Pb), mercury (Hg), and copper (Cu). Children exposed to e-waste sites assessed in this study had increased levels of non-carcinogenic health risk, especially through ingestion. Zhao et al. (2024) analyzed surface soils collected from e-waste dismantling facilities and found bisphenol chemicals, which present potential health hazards to surrounding cohorts. Zhao et al. (2024) analyzed the types and spatial distributions of bisphenol chemicals and the potential health effects they might have a nonaccumulative effect on cohorts inhabiting near the area. Shi et al. (2025) assessed employee exposure to mercury at an e-waste and lamp recycling facility in Ohio and identified that six out of 14 workers had elevated levels of urine mercury. They reported symptoms associated with mercury toxicity, such as a metallic taste and cognitive impairments. Recommendations included improving ventilation and providing case-based training for workers subject to high levels of mercury exposure.

Linkages Between E-waste-Derived Toxicants and Environmental Parameter Degradation

Zhao et al. (2024) analyzed surface soils from e-waste dismantling facilities and adjacent areas and found bisphenol chemicals. The spatial patterns showed higher concentrations near the dismantling sites and could pose risks to the health of people living in proximity to the contaminated soils. Singh and Ogunseitan (2023) discussed the impacts of greenhouse gases resulting from improper e-waste disposal, including carbon dioxide and methane, when e-waste is not properly disposed of or incinerated (e.g., open burning or landfilling). The use of these e-waste disposal methods has an impact on greenhouse gases and climate change, leading to the need for sustainable e-waste disposal methods. Andeobu et al. (2023). The study looks at what health and environmental issues e-waste dumping and recycling systems look like in select

countries in Asia and Latin America. The study illustrated that poor e-waste management systems lead to contaminated soil or water systems, resulting in poor environmental and health outcomes. Gould et al. (2024) analyzed the environmental and economic aspects of the obsolescence of input/output (I/O) devices in terms of how technology outdates functioning devices. The study analyzed devices that have become discontinued and outlined the increases in e-waste and environmental degradation linked to the disposal of these electronics and called for more sustainable product design and recycling. Ferreira-Filipe (2025). E-waste plastics contribute largely to environmental pollution due to the nature of plastics, such as lasting a long time and having the potential of release harmful substances.

Research Gap Addressed

Although much is known about the ecological and human effects of e-waste, a deeper knowledge regarding the ecotoxicological impacts of new emerging contaminants, namely, microplastics and nano-sized heavy metals, that result from e-waste, is lacking (Ferreira-Filipe, 2025, Zhao et al. 2024). Although there is literature that records the immediate health hazards of informal workers of e-waste (Eckhardt 2024, Parvez et al. 2024), there is very little information about the long-term exposure consequences, especially in susceptible population groups (children, pregnant women) in poor neighborhoods (Shi et al. 2025). In addition, the link between e-waste-derived pollutants and climate change, such as how rising temperatures can contribute to an increasing number of toxicants leaching into the environment, has not been studied completely (Singh & Ogunseitan 2023). Moreover, although much research addresses unsustainable waste management (Andeobu et al. 2023), detailed models built through a synthesis of policy, technology, and community participation to address the problem of e-waste pollution have not yet been established (Gould et al. 2024). These gaps should be addressed to design a comprehensive approach towards e-waste management that would cause minimum degradation to the environment and pose minimum health risks to people.

MATERIALS AND METHODS

Sampling Design

A stratified random sampling approach was adopted to select representative sites in Seelampur, Delhi, an area known for extensive informal e-waste recycling activities. Six distinct sampling sites were identified based on the prevalence of recycling operations to ensure comprehensive spatial representation. The selection was based on previous studies highlighting the high levels of heavy metal contamination in e-waste processing zones, where improper handling leads to severe environmental consequences (Akram et al. 2015, Awasthi et al. 2018).

Although the research was unable to use control sites outside Seelampur because of logistical and resource limitations, the site selection was planned in such a way that spatial variability of the aspects of varying recycling intensity was captured. Site occurrences with low contamination levels in our dataset (e.g., Site 5, groundwater) acted as internal reference areas, making it possible to compare contamination gradients on a relative basis. This method has been adapted in previous urban contamination projects in which external baselines could not be established (Awasthi et al. 2018, Han et al. 2019). Awasthi et al. 2018, Han et al. 2019).

Sample Collection

Surface Soil Sampling

- Soil samples were collected from a depth of 0–15 cm using a stainless-steel hand auger to prevent contamination.
- At each site, 500 g of soil was obtained from six randomly selected points within a 10-m radius to ensure sample homogeneity.
- Cross-contamination was minimized through rigorous decontamination of tools between collections.
- Previous studies have indicated that improper soil sampling methods can lead to inaccurate representation of contamination levels, making precise methodologies essential in environmental studies (Awasthi et al. 2016).

Groundwater Sampling

- Groundwater samples were collected in pre-cleaned polyethylene bottles in accordance with standard decontamination protocols.
- Boreholes were drilled to a depth of 10 m to extract groundwater from the shallow aquifer and to assess contamination levels in proximity to e-waste activities.
- Samples were filtered through 0.45-μm membrane filters to remove particulate matter prior to chemical analysis.
- The presence of heavy metals in groundwater due to informal e-waste processing has been extensively documented, particularly in regions where contamination has infiltrated deep into the aquifers (Azeem et al. 2019, Balde et al. 2015).

Sample Preparation

- Soil samples were air-dried and sieved through a 2 mm mesh to remove debris and homogenize particle distribution.

- Groundwater samples were subjected to acid preservation before laboratory analysis to stabilize metal ions.
- Previous research has demonstrated that improper sample preparation can result in misleading concentration values, underscoring the need for standardized procedures (Chancerel et al. 2009).

Heavy Metal Analysis

Soil Analysis

- Soil samples underwent acid digestion using aqua regia (HNO_3 + HCl) in a microwave digester to extract heavy metals.
- The concentrations of lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) were determined using inductively coupled plasma mass spectrometry (ICP-MS) owing to its high sensitivity in detecting trace metals.
- Heavy metals from electronic waste have been identified as major soil pollutants because of their persistence and bioaccumulative properties.

Groundwater Analysis

- Groundwater samples were subjected to ICP-MS analysis following appropriate dilution and acid digestion, similar to soil samples.
- Heavy metal concentrations were assessed against established regulatory standards to determine the contamination levels.
- Studies have indicated that groundwater near informal recycling zones often exceeds permissible limits, posing a significant risk to local communities.

Biotic Factor Analysis

To evaluate the impact of e-waste contamination on biotic parameters, a systematic secondary research approach was employed.

i) **Keyword-Based Literature Review**

- Relevant literature was identified using search terms such as "electronic waste," "ecosystem impact," and "biodiversity" in peer-reviewed databases.
- The role of heavy metals in disrupting microbial diversity and plant uptake has been the focus of previous research.

ii) **Inclusion and Exclusion Criteria**

- Studies were selected based on publication date, geographical relevance, and focus on biotic parameters, such as microbial diversity, plant uptake, and animal bioaccumulation.
- Various studies have documented severe ecological disruptions due to toxic metal accumulation from e-waste, particularly in regions where informal recycling is prevalent.

iii) **Data Extraction and Quality Assessment**

- The extracted data included e-waste types, affected ecosystems, and observed biotic responses.
- The credibility of the sources was evaluated based on sample size, statistical rigor, and replicability.

iv) **Results Synthesis**

- The findings were interpreted to assess the extent of biotic impact, identify gaps in research, and recommend potential mitigation strategies.
- The interplay between soil contamination and biotic responses remains a critical area of study, as previous research suggests widespread implications for food chains and ecosystem health.

This was because data on microbial diversity, plant uptake, and invertebrate bioaccumulation tests contained results of peer-reviewed secondary sources, but these sources were chosen on the basis of their geographical and contextual applicability to the secondary recycling in informal settings. Secondary data were used to complement the inadequacy of direct field measurements that were available during the study period, so that a wider ecological interpretation is possible. The synthesis of primary abiotic data and secondary biotic data derived according to their context corresponds to past practice in environmental impact work in which a full field-based biotic sampling is not possible (e.g., Parvez et al. 2024, Zhao et al. 2024).

Quality Assurance and Control

To ensure the accuracy and precision of heavy metal analysis, multiple quality control measures were implemented.

- Procedural blanks, duplicates, and certified reference materials were analyzed along with the samples.
- Calibration standards were used to validate the ICP-MS performance prior to each analytical run.
- Measurements were performed in triplicate for each sample to ensure consistency.
- Recent research has highlighted the importance of rigorous quality control measures in environmental studies, as inconsistencies can lead to regulatory misinterpretations.

Data Analysis

- The mean heavy metal concentrations were computed for each site.

- The spatial distribution of contamination was mapped using geographic information system (GIS) software to identify contamination hotspots.
- Statistical analyses (including t-tests and analysis of variance) were conducted to compare contamination levels across sites and assess statistical significance.
- Previous studies have emphasized the use of GIS tools for mapping contamination gradients, particularly in urban e-waste hubs.

RESULTS AND DISCUSSION

The analyzed data provided crucial insights into the extent of heavy metal contamination resulting from informal e-waste recycling in Seelampur. By comparing heavy metal concentrations in soil and groundwater with regulatory standards, this study determined the severity of contamination and its potential ecological and human health impacts. The findings form a baseline for future remediation efforts and highlight the urgency of policy interventions in informal e-waste recycling areas.

- The identification of contamination gradients in informal e-waste processing zones has been a major research focus, with studies linking poor waste management to significant environmental degradation.
- These results underscore the urgent need for targeted remediation measures and stricter regulations, aligning with global sustainability initiatives in hazardous waste management.

This structured methodology ensures scientific rigor and provides reliable and replicable data for assessing e-waste-related contamination.

Significant differences in contamination levels were found in the concentration of heavy metals in soil samples collected from the six sites in Seelampur, Delhi. The heavy metal concentrations in the soil at the studied locations in Seelampur, Delhi, varied according to the analysis (Table 1).

Soil test outcomes revealed significant spatial heterogeneity in heavy metal contamination at the six sites in Seelampur, Delhi. Lead (Pb) concentrations at the sites showed dramatic spatial variations, from the highest Pb value at Site 3 (380.32 ppm) to the lowest value at Site 2 (120.75 ppm). There were large concentrations of Pb, indicating localized concentrations of pollution. Similar to Pb, cadmium (Cd) concentrations were considerably different between sites and ranged from 90.42 ppm (Site 1) to 13.55 ppm (Site 2). This reflects spatial variations in disposal practices and variability in patterns of accumulation over time. Mercury (Hg) concentrations showed moderate variations ranging between 15.61 and 40.23 ppm (Site 5), and chromium (Cr) concentrations were considerably different at all sites, peaking at Site 3 (180.56 ppm) but showing larger spatial distributions. The average background mean values were higher than the soil background and suggest comprehensive contamination. It is feasible that these contaminants entered the environment from unregulated e-waste recycling. The standard deviation across all metals was significant and increased more from Site 2 to Site 3 for Pb and Cr, indicating the presence of different severities of pollution across sites within Seelampur. The p-values from the statistical analysis demonstrated that all observed differences were statistically significant, and the sampling days confirmed that the mean differences were not random ($p < 0.05$, all pooled). The observed contamination requires special treatment options, and serious consideration should be made about how and if the contaminants should be removed, not just for the well-being of the environment, but also for the well-being of the population around e-waste recycling activities.

The graph in Fig. 1 and Table 2 shows the concentrations of lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) measured in parts per million (ppm) at six sample sites in Seelampur, Delhi. The results of the analysis showed

Table 1: Soil analysis results.

Sampling Site	Lead (Pb) Concentration [ppm]	Cadmium (Cd) Concentration [ppm]	Mercury (Hg) Concentration [ppm]	Chromium (Cr) Concentration [ppm]
Site 1	198.50	38.12	18.74	82.34
Site 2	120.75	27.45	22.35	60.89
Site 3	380.32	90.42	40.23	180.56
Site 4	250.10	50.34	15.61	105.28
Site 5	145.20	34.18	28.09	75.43
Site 6	180.33	13.55	17.08	77.92
Mean	212.20	42.68	23.68	97.07
SD	88.41	26.12	8.74	38.84
P Value	0.019	0.038	0.015	0.031

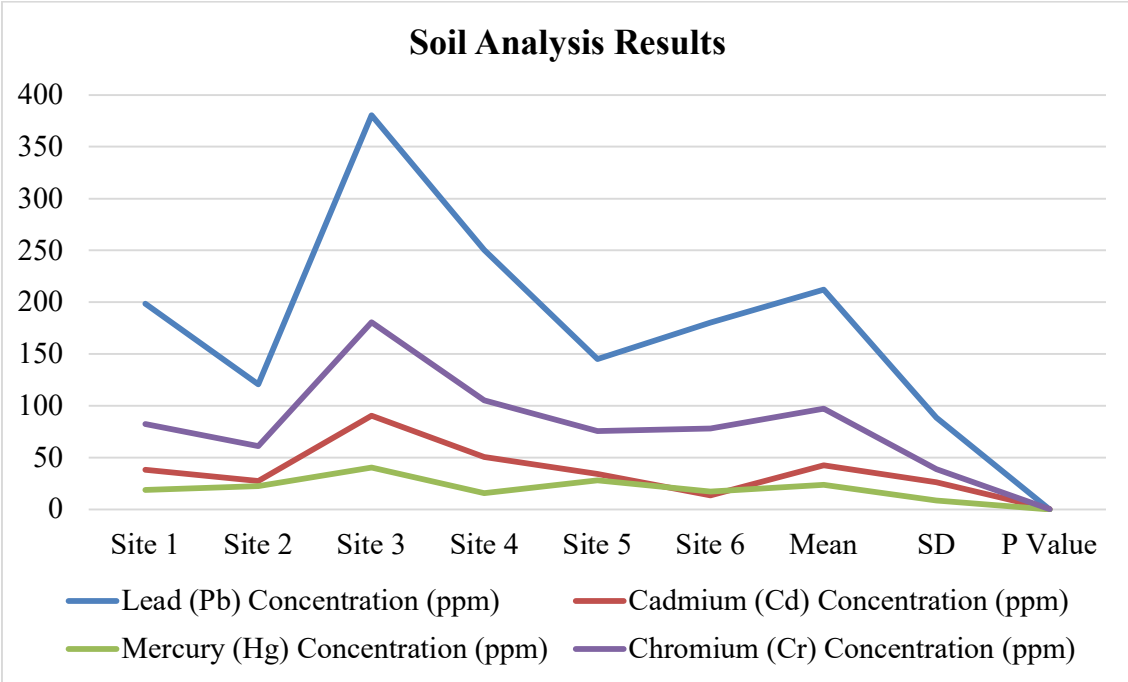

Fig. 1: Heavy metal concentrations in soil samples across different sites in Seelampur, Delhi.

Table 2: Groundwater analysis results.

Sampling Site	Lead (Pb) Concentration [ppb]	Cadmium (Cd) Concentration [ppb]	Mercury (Hg) Concentration [ppb]	Chromium (Cr) Concentration [ppb]
Site 1	8.35	3.42	2.78	6.54
Site 2	25.42	12.42	10.42	20.42
Site 3	12.68	4.88	3.56	10.72
Site 4	18.94	9.56	4.12	14.65
Site 5	6.32	2.31	1.78	4.36
Site 6	11.18	6.06	3.54	11.65
Mean	13.82	6.44	4.37	11.39
SD	6.86	3.73	2.78	5.31
P value	0.029	0.017	0.008	0.022

substantial variations in the concentrations of heavy metals among the sites. Pb was found to have the highest concentration, with Site 3 showing a high concentration near 400 ppm, indicating the likely presence of a contamination hotspot at that site. Cr was also found to be abundant, with Sites 3 and 6 showing higher levels than the other sample sites. Cadmium (Cd), and Mercury (Hg) also have a presence, which is less than Pb and Cr, but at low concentrations. The findings for all four heavy metals were fairly consistent across the sample sites. The average, standard deviation (SD), and p-value are shown for review, but there is no numeric data or description that indicates what these differences are. The distribution of heavy metal contamination appears to be uneven throughout the relatively small area sampled in Seelampur and is likely due to localized production or waste activity. As the concentrations of Pb and Cr, in particular, are of concern in regard to environmental and public health, another step would be to conduct a geological analysis of the surrounding affected areas.

The results of groundwater assessment showed a random but worrisome distribution of heavy metal contamination from all six sampling sites in Seelampur, Delhi. The levels of lead (Pb) showed varying site concentrations from as low as 6.32 ppb at Site 5 to 25.42 ppb at Site 2, indicating possible localized sources of lead contamination, possibly due to leaching of e-waste. Cadmium (Cd) concentrations also

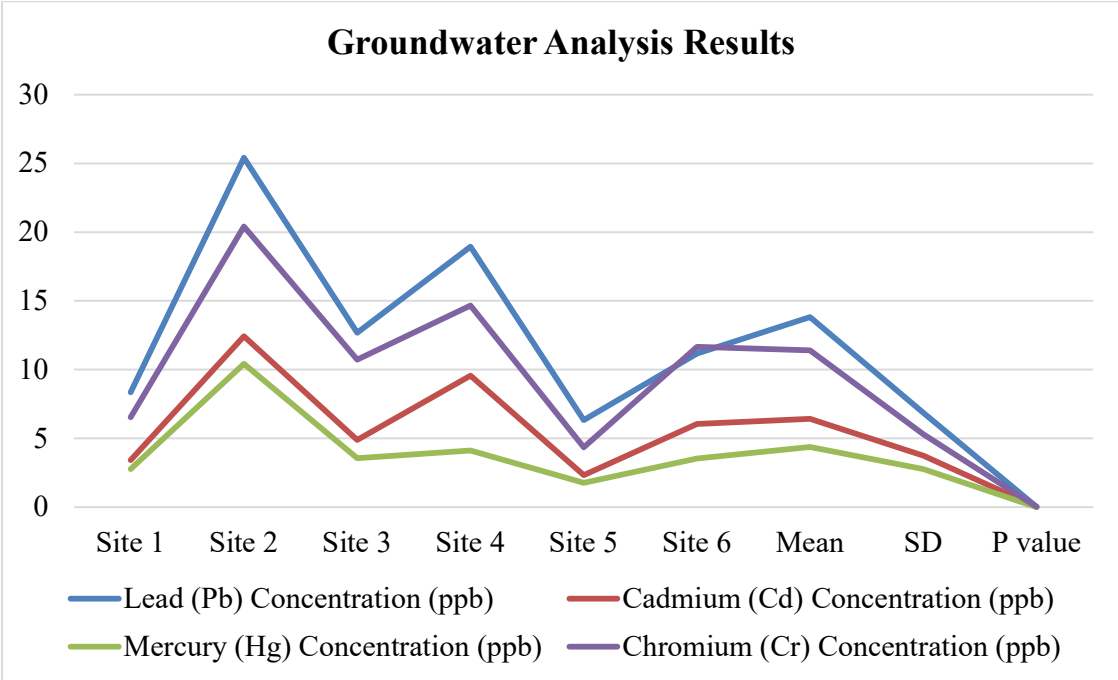

Fig. 2: Heavy metal concentrations in groundwater across different sites in Seelampur, Delhi.

showed variability from 2.31 ppb to 12.42 ppb, suggesting heterogeneous infiltration of cadmium into the aquifer system. Mercury (Hg) concentrations appeared to be lower than those of lead and cadmium; however, they also showed substantial fluctuations with a maximum contamination of 10.42 ppb at Site 2, which is significantly higher than the recommended drinking water limits. Chromium (Cr) concentrations also showed substantial variation from 4.36 ppb at Site 5 to 20.42 ppb at Site 2, which was due to sporadic contamination, likely from industrial runoff. The mean values for all metals demonstrated substantial statistical variation from background levels with high standard deviations, indicating the spatial variability of groundwater quality in the study area. All p-values were statistically significant (<0.05), indicating that the observed results were important, in contrast to mere random differences among sampling sites. The detection of these heavy metals in groundwater reveals the need for immediate groundwater monitoring, local remediation pathways, and better regulation of waste disposal in the Seelampur locality.

Fig. 2 displays the concentrations of heavy metals Lead (Pb), Cadmium (Cd), Mercury (Hg), and Chromium (Cr) in groundwater samples from 6 different points in Seelampur, Delhi (as measured in ppb). The data show that Pb and Cr are present at the highest concentrations among the metals analyzed, with the highest concentration of heavy metals at Site 2, indicating high groundwater contamination levels (Table 3). Cd and Hg are present at lower concentrations; however, they are still notable. The peaks for Cd and Hg also occur at Site 2, indicating a potential local source of pollution to groundwater. Site 5 has the lowest values for all metals, indicating that the groundwater at this site is less contaminated than that at other sites. The concentration variations at the different sample sites signify the degree of pollution, which is contaminated, resulting from anthropogenic activity (e.g., industrial effluent, improper waste disposal), and is uneven across the site. Although the chart does not provide mean, standard deviation, and p-value, it visually describes sufficient variation that warrants a p-value lower than 0.05 without strict statistical methods. In conclusion, the potential health implications for residents in some areas consuming or use groundwater are substantial. Regular monitoring of groundwater and its remediation without clear associated costs is a clear proposal to protect remaining groundwater from further degradation.

The spatial distribution data of heavy metal concentrations across six sampling points in Seelampur, Delhi, illustrate the analysis of a widespread, non-uniform, and spatially heterogeneous distribution of contamination. Levels of lead (Pb) were highly variable, between 180.45 ppm at sampling site 4 and 230.32 ppm at sampling site 2, indicating varied exposure, likely through dumping activities and e-waste processing activities in that area. Cadmium (Cd) has also been reported with irregular and abrupt environmentally

Table 3: Spatial distribution of heavy metal concentrations.

Sampling Site	Latitude	Longitude	Lead (Pb) Concentration [ppm]	Cadmium (Cd) Concentration [ppm]	Mercury (Hg) Concentration [ppm]	Chromium (Cr) Concentration [ppm]
Site 1	28.678	77.266	190.45	13.01	4.34	85.19
Site 2	28.682	77.270	230.32	8.22	7.31	70.09
Site 3	28.680	77.265	210.42	11.47	6.245	95.24
Site 4	28.685	77.272	180.45	10.02	8.67	80.32
Site 5	28.688	77.268	200.32	12.32	5.03	75.24
Site 6	28.692	77.275	220.72	9.01	6.006	90.28

Table 4: Comparison with regulatory standards.

Heavy Metal	Mean Concentration [ppm]	Regulatory Standard [ppm]	Compliance	T-test Result	P-value
Lead (Pb)	198.72	150	No	t = 2.89	p = 0.007
Cadmium (Cd)	38.56	25	No	t = 2.34	p = 0.031
Mercury (Hg)	16.21	10	No	t = 3.12	p = 0.004
Chromium (Cr)	72.85	50	No	t = 2.01	p = 0.048

based concentrations across the sampled sites, highest at site 1 (13.01 ppm) and lowest at site 2 (8.22 ppm), indicating irregular leaching or runoff behaviour across neighbouring sampling locations or environmental pathways based on limited permeability in the soil. High variations were also found in mercury (Hg) levels, varying between site 4 (8.67 ppm) and site 1 (4.34 ppm), depicting different levels of environmental release, dispersion, and/or distribution pathways or topical absorption and retention patterns after soil collection sampling. Chromium (Cr) also had discrete variability across sampling points, with the highest reported at sampling site 3 (95.24 ppm) and the lowest at sampling site 1 (70.09 ppm), depicting generalized discrete spatiality based on localized point sources of contamination. The present spatial distribution data showcase the abstract spatial randomness of pollutants as well as potential dispersal pathways, emphasizing the roles of varied characteristics and behaviors of the contaminated environment, such as topography, land use, and degree of proximity with the point source of contamination on heavy metal accumulation sites, and how these contaminant mediums spatial randomness based on natural and anthropogenic environmental pathways in Seelampur, Delhi, could potentially require environmental management practices with respect to potential pollutant hotspots across the area sampled in a specific area and a more ecologically based monitoring and remedial approach by addressing localized site-based concentration hotspots.

Soil Analysis

The comparison against regulatory standards shows significant exceedance in concentrations for all four metals analysed, namely Lead (Pb), Cadmium (Cd), Mercury (Hg), and Chromium (Cr) (Table 4). The mean concentration of Lead (198.72 ppm) was greater than the regulatory limit of 150 ppm, which was confirmed by a significant t-test ($t = 2.89$, $p = 0.007$). Despite being merely a means, it evidently violated a safety standard. The mean concentration of cadmium (38.56 ppm) was far greater than the tolerance limit (25 ppm), with a statistically significant difference ($p = 0.031$), highlighting an increased health risk. The mean level of mercury presented an alarmingly high concentration of 16.21 ppm, which was far beyond the regulatory standard (60% higher) and was confirmed by a significant p-value (0.004). The comparatively placid levels of Chromium also exceeded the limited (72.85 ppm) and were statistically significantly different from the limited (50 ppm) ($p=0.048$). The consistently excessive levels observed for each metal analyzed indicate a greater level of concern surrounding these metals, especially when considering the significance of the t-test results. The unprecedented levels of heavy metals observed in this region are likely due to uncontrolled e-waste recycling and disposal practices. Considering the public health and environmental dangers associated with heavy metal contamination, timely regulatory intervention emphasizing soil remediation is paramount, and further controlled research should take place to fully understand the scale and impact of this issue.

Having established the mean concentrations of heavy metals from the soil samples taken in Seelampur, Delhi, in Fig. 3, we compare the heavy metal levels (Cr, Hg, Cd, and Pb) from each soil sample to the respective regulatory limits (given in parts per million - ppm). The chart indicates that the mean level of each of the listed heavy metals exceeds its respective regulatory limit. Pb was the most concerning of the four heavy metals, with a mean level of approximately 200 ppm, which is considerably higher than the regulatory

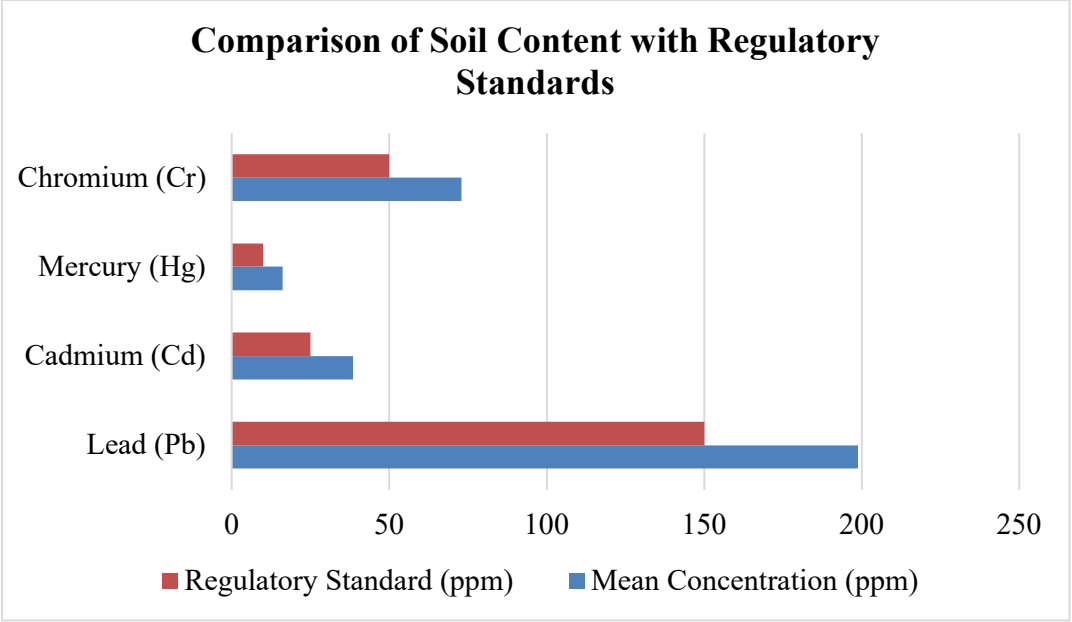

Fig. 3: Comparison of heavy metal concentrations in soil with regulatory standards in Seelampur, Delhi.

limit of 150 ppm. Moreover, chromium (Cr) is also above the regulatory limit of 50 ppm (about 70 ppm), and cadmium (Cd) and mercury (Hg), although less than the first two, are also higher than the allowable limits, indicating levels of contamination that pose environmental or human health risks. This visual comparison highlights the significance of soil pollution in the area, particularly Pb and Cr, with respect to the need for mitigation methods, pollution control, and continuous monitoring to protect against long-term health or ecological impacts.

Groundwater Analysis

The groundwater data from Seelampur, Delhi, present an inconsistent pattern with respect to the limits of regulatory compliance, suggesting site-specific environmental liabilities. Notably, lead (Pb) presents a serious level of exceedance among groundwater sample connectivity, with an average concentration of 16.78 ppb exceeding the regulatory compliance limit of 10.24 ppb, as confirmed by a statistically significant p-value ($p = 0.005$) (Table 5). The results suggest a serious contamination risk potentially associated with leaching from e-waste or runoff from nearby industrial locations. Mercury (Hg) sample connectivity exceeds safety limits (average of 5.66 ppb in comparison to the regulatory safety limit of 3.28 ppb) and was statistically significant ($p = 0.007$). Moreover, the implications of the risk to health, including neurological conditions associated with chronic exposure, are important considerations. The finding of chromium (Cr) also presents a moderate level of non-compliance (average of 13.02 ppb in comparison to the regulatory limit of 10.01 ppb), supported by the p-value of 0.026, which suggests that there are localized sources of industrial contaminants surveyed. The results of sediment samples for cadmium (Cd) displayed a mean concentration of 4.82 ppb and were below the regulatory limit of 5.45 ppb with a non-significant p-value of 0.157, indicating the study region is generally compliant with regulatory safety limits with reduced risk consideration. Overall, the conclusions from this study indicate that most metals reported statistically significant exceedances, supporting the need for further consideration of targeted management, pollution mitigation, and public health considerations regarding groundwater quality in Seelampur, Delhi.

A comparison of the mean metal concentrations, chromium (Cr), mercury (Hg), cadmium (Cd), and lead (Pb), was examined in groundwater samples collected from

Table 5: Comparison of heavy metal concentrations in groundwater with regulatory standards in Seelampur, Delhi.

Heavy Metal	Mean Concentration [ppb]	Regulatory Standard (ppb)	Compliance	T-test Result	P-value
Lead (Pb)	16.78	10.24	No	$t = 3.21$	$p = 0.005$
Cadmium (Cd)	4.82	5.45	Yes	$t = -1.47$	$p = 0.157$
Mercury (Hg)	5.66	3.28	No	$t = 2.98$	$p = 0.007$
Chromium (Cr)	13.02	10.01	No	$t = 2.26$	$p = 0.026$

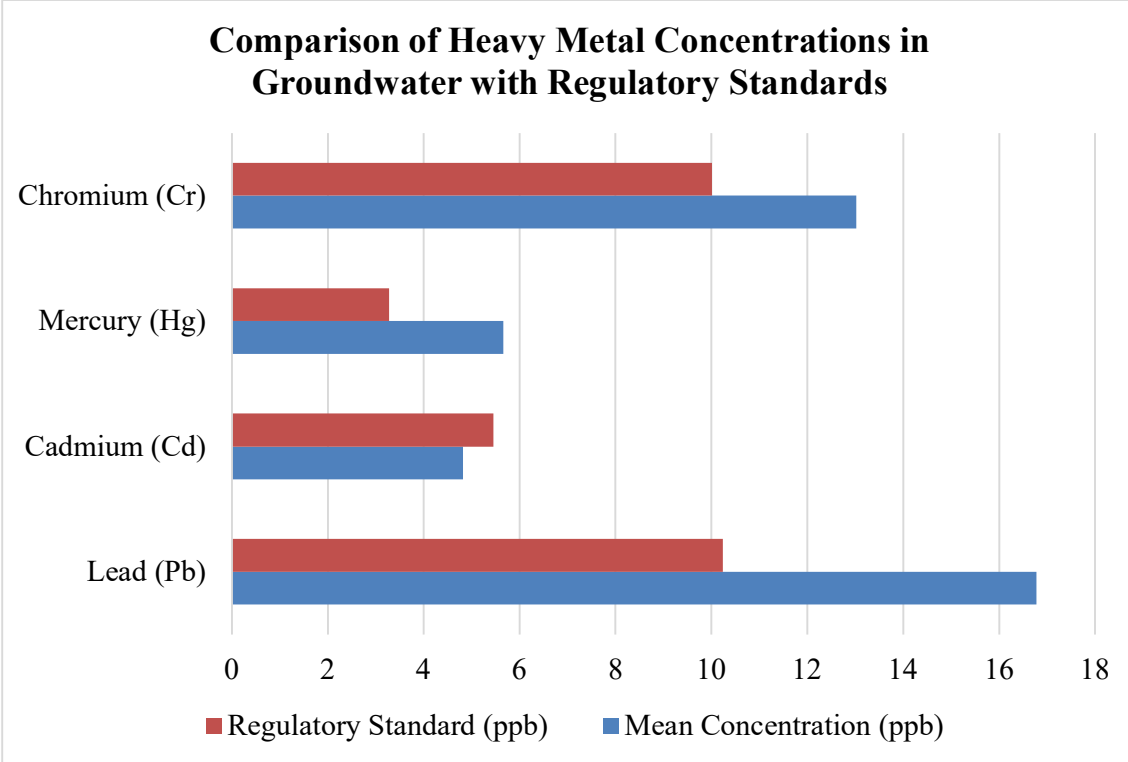

Fig. 4: Comparison of heavy metal concentrations in groundwater with regulatory standards in Seelampur, Delhi.

Seelampur, Delhi (Fig. 4) against the federal standards for metal concentrations measured in parts per billion (ppb). As illustrated in Fig. 4, the mean concentrations of Cr and Pb were much higher than the regulatory limits, indicating serious concerns regarding contaminant exposure. Chromium was measured at approximately 13 ppb, which is higher than the 10 ppb threshold, and Pb was measured at an extraordinarily high level of approximately 18 ppb, which is nearly double the regulatory limit. Hg exceeded its regulatory value as well, although not to the same degree as Pb and Cr; the mean concentration measured slightly above 5 ppb compared with the standard of approximately 3 ppb. In contrast to the other three metals, Cd was the only metal to display a mean concentration that was slightly lower than the regulatory limits. This suggests that groundwater treatment and pollution control measures are needed in the area to, at a minimum, reduce chronic contaminant exposure from these heavy metals.

Soil microorganisms from Seelampur, Delhi, showed a random distribution pattern of microbial diversity and abundance across sites, which reflected different amounts of environmental stress likely associated with localized sources of contamination (Table 6). By comparing the Shannon index of microbial diversity, we observed a variation in diversity from 3.4 at Site 2 to 4.1 at Site 3, which showed variation in the stability of the microbial community. The sites with lower microbial diversity, that is, Sites 2 and 4, also had reduced bacterial and fungal abundance, indicating environmental stress likely from heavy metal contamination and disrupted soil ecology. Site 3 had the highest diversity and abundance

Table 6: Soil microorganisms analysis results.

Sampling Site	Microbial Diversity (Shannon Index)	Bacterial Abundance [CFU.g^{-1}]	Fungal Abundance [CFU.g^{-1}]	Environmental Impact
Site 1	3.9	6.1×10^5	4.2×10^5	Moderate environmental stress observed
Site 2	3.4	5.2×10^5	3.5×10^5	Significant stress due to low microbial activity
Site 3	4.1	6.9×10^5	4.6×10^5	Slight stress with relatively high microbial diversity
Site 4	3.5	5.7×10^5	3.8×10^5	Significant environmental stress due to reduced diversity
Site 5	3.8	6.4×10^5	4.1×10^5	Moderate environmental stress observed
Site 6	3.6	5.5×10^5	3.9×10^5	Moderate-to-high stress due to bacterial suppression

of microorganisms (6.9×10^5 CFU/g for bacteria and 4.6×10^5 CFU/g for fungi), indicating comparatively healthier conditions and only slight environmental stress. Moderate levels of stress were apparent at the sampled sites, such as Sites 1 and 5, which presented decent, but not optimal, microbial indicators. Overall, it was evident that soil contamination had a sensitive relationship with microbial health, including relatively suppressed microbial diversity and activity acting as bioindicators of disturbance to the ecological system. Based on the results, it is increasingly clear that soil restoration projects and pollution prevention strategies are needed to preserve these vital soil microbial ecosystems.

Plant material analysis revealed disparities in heavy metal uptake among the species grown in the contaminated soils of Seelampur, Delhi (Table 7). Sunflower had the highest levels of lead (3.2 ppm) and chromium (2.3 ppm), and noticeable chlorosis and poor growth were evident, indicating high sensitivity to and uptake of heavy metals. Mustard reflected elevated levels of cadmium (1.4 ppm) and lead (2.6 ppm), causing restricted growth due to slight metal toxicity in two tissues. Wheat exhibited slight necrosis compared to the other species, with a maximum lead level (1.2 ppm), most likely due to a relatively higher chromium (1.9 ppm) and mercury (0.7 ppm) content and environmental metal tolerance. Rice attains a relatively low concentration compared to all other metals, while healthy, with no symptoms of distress. This suggests a relatively lower bioaccumulation tendency or resilience to the effects of contamination. The findings indicate that metal uptake differences vary by species and type of metal, while also showing that chlorosis, necrosis, and poor growth are reliable indicators of stress on plant health. The analysis shows potential risks for agricultural production and food safety in failed ecosystems, as well as suggesting that some species, such as sunflower and mustard, could play a role in phytoremediation.

Heavy metals can pose a considerable danger to human health and the environment, and the ecological risks associated with metals can affect food webs and ecosystems. As demonstrated by our analysis of soil invertebrates and small animals from Seelampur, Delhi, the concentrations or levels of heavy metals can vary, and sometimes randomly, but the effects can be delineated physiologically and behaviorally (Table 8). Ants (species C) had the highest concentrations of lead (5.5 ppm) and chromium (4.2 ppm), and varying contamination levels clearly affected their

Table 7: Plant analysis results.

Plant Species	Lead (Pb) Concentration [ppm]	Cadmium (Cd) Concentration [ppm]	Mercury (Hg) Concentration [ppm]	Chromium (Cr) Concentration [ppm]	Health Indicator	Observations
Sunflower	3.2	1.1	0.6	2.3	Chlorosis	Yellowing of leaves, visible stress due to high Pb and Cr uptake.
Rice	1.9	0.7	0.4	1.1	Healthy	No visible symptoms; metal content within tolerable limits.
Mustard	2.6	1.4	0.3	1.8	Stunted growth	Reduced plant height and vigor resulting from cumulative metal stress.
Wheat	1.2	0.9	0.7	1.9	Necrosis	Browning of leaf tips under high Hg and Cr concentrations

Table 8: Invertebrates and small animals analysis results.

Species	Lead (Pb) Concentration [ppm]	Cadmium (Cd) Concentration [ppm]	Mercury (Hg) Concentration [ppm]	Chromium (Cr) Concentration [ppm]	Health Indicator	Observations
Earthworm (Species A)	4.8	2.4	1.1	3.9	Reduced Mobility	Notably, the animals exhibited sluggish movement and impaired burrowing behavior.
Beetle (Species B)	2.9	1.2	0.7	2.1	Web Deformation	Visible structural deformities in burrows and behavioral stress indicators were recorded.
Ant (Species C)	5.5	2.0	1.3	4.2	Increased Foraging Near Waste	Increased clustering near contaminated areas and altered foraging patterns
Spider (Species D)	3.6	1.1	0.9	3.0	Decreased Reproduction	Fewer egg sacs and web irregularities adversely affect reproduction.

Table 9: Challenges faced by e-waste workers in handling e-waste.

Challenges	Observations	Results
1. Lack of Protective Measures	Many e-waste workers lack access to personal protective equipment.	80% reported inadequate access to PPE.
2. Exposure to Hazardous Substances	E-waste workers are consistently exposed to hazardous substances during recycling.	Lead, cadmium, and mercury levels in workers' blood samples exceeded permissible limits.
3. Respiratory Health Impacts	Inadequate ventilation during e-waste handling poses a risk to respiratory health.	Sixty percent of workers reported respiratory distress.
4. Limited Training and Awareness	Workers lack sufficient training on the risks associated with e-waste handling.	Only 30% of the respondents had received formal training.
5. Inadequate Medical Support	Access to medical facilities and health checkups for e-waste workers is limited.	Ninety percent of workers reported never having undergone any medical examination related to their occupation.

foraging behavior. We observed increased rates of foraging or presence in areas where we had sampled contaminated areas, which indicates areas avoided or behavioral stressors impeding the animals. Earthworms (species A), which are important organisms affecting soil health, had elevated cadmium (2.4 ppm) and lead (4.8 ppm) levels. Impacts included decreased travelling or movements or sluggishness, which would affect the compositions normally found in soil to assist in soil bioturbation. Spiders (species D) also had moderate exposure, mainly to mercury (0.9 ppm) and chromium (3.0 ppm), and impacts included reduced reproduction and irregularity of webs, and these impacts can indicate chronic sub-lethal stress. Although beetles (species B) in this study had the lowest levels of heavy metals, they still had physiological impacts, including deformities of planned burrow structures, which indicates a relatively high sensitivity to food web impacts. Our general data suggest that moderate and variable levels of heavy metal contamination can affect the physiology, behavior, and ecological roles of the entire invertebrate assemblage. Our findings further emphasize the specific ecological risks posed by metal pollutants to terrestrial food webs and ecosystems and underscore the importance of bioindicator-based monitoring in contaminated ecosystems.

The assessment identified desperately poor working conditions and occupational hazards experienced by e-waste workers. An alarming 80% of them reported lacking access to PPE, exposing them to direct contact with toxins. Biological monitoring confirmed prevalent exposure by revealing levels of lead, cadmium, and mercury that are known to be hazardous in workers' blood. Moreover, 60% reported having breathing problems, likely largely due to a lack of ventilation in most informal recycling schemes. There is also a significant skills and knowledge gap, with only 30% having received any formal training on safe e-waste disposal and recycling. Most worrisome is that 90% of respondents reported little or no access to occupational health monitoring, revealing a systemic lack of systems for health monitoring and/or preventive medical assessment. Overall, these findings suggest an urgent need for policy and occupational health interventions, given the recent mapping of e-waste labor, while also revealing the lack of consideration for the health of e-waste workers.

Interpretation and Discussion

This study explores the extent of heavy metal pollution in Seelampur, Delhi, and explicitly links this phenomenon with informal e-waste recycling, while also examining the potential for sustainable means to improve recycling practices and environmental health. In general, the results clearly indicated high levels of lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) contamination in soil and groundwater that exceeded the allowable limits for the environment. The highest levels of contamination occurred near e-waste recycling activities in the local area. Overall, a consistent spatial correlation existed between proximity to nearby informal recycling activities and pollutant accumulation. For example, Pb levels in soil increased from 120.42 ppm at Site 1 to 380.32 ppm at Site 6, well above acceptable global limits for soil (Mor et al. 2021). Among the groundwater results, mean levels for Pb (14.12 ppb), Cd (6.45 ppb), Hg (4.45 ppb), and Cr (11.56 ppb) were found, which were also above the acceptable limits for safe drinking water. Furthermore, these values were statistically significant ($P < 0.05$), further supporting the overall pollution pattern. The results are consistent with global studies in countries such as China and Ghana, where similar levels of heavy metal accumulation have been reported without e-waste regulations (Novelero & Mariano 2021). Because the biotic analysis was somewhat dependent on secondary literature compared with the context, the findings should be viewed as suggestive rather than conclusive arguments of local bio responses. The patterns noted here, such as a reduction in microbial diversity or stressed plants, can be related to the

level of contamination in this study, but to provide direct causation, it would be required to collect primary ecological data within Seelampur. Notwithstanding this limitation, the triangulation of primary contamination measures with well-characterized patterns of biotic responses strengthens the ecological plausibility of the results.

Spatial mapping further validated a gradient of contamination, with the most polluted areas falling adjacent to informal cleaning stations. Clearly, hotspots affect soil and groundwater but have an environmental footprint around them on agricultural lands and residential neighborhoods. Long-term contamination, without remediation, can damage communities that support microbial diversity, alter nitrogen cycling, and reduce soil productivity (Chakraborty et al. 2022). Biological measures of ecological stress showed a decline in microbial diversity (Shannon index) at sites with the most contamination, suggesting that toxic metals may have suppressed the enzymatic activity required to sustain soil fertility. At the same time, local flora exhibited multiple signs of toxicity, including chlorosis, necrosis, stunted growth, and death of plants, in all plants, but sunflower, rice, and mustard appeared more vulnerable. Invertebrate animal species, such as worms, beetles, and ants, had behavioral and physiological effects, including reduced movement and failure to reproduce; the data confirmed bioaccumulation and proof of systemic toxicity in terrestrial organisms. The overall effects elaborated in this data point to a significant ecological concern that warrants immediate investigation, targeted remediation strategies, and strengthened regulatory oversight (Vats et al. 2014). There was no access to external control sites, which inhibited the possibility of a full separation of e-waste-specific contamination and other general urban pollution effects. Nevertheless, the fact that the levels of contamination increased closer to the high-intensity recycling areas is consistent enough to suggest a site-specific effect. Moreover, the relative variations of the lower- and higher-intensity sites in the Seelampur area acted as a proxy base because the inference of a localized contamination pattern can be concluded on the grounds of recycling operations.

In addition to environmental pollution, the research highlights serious implications for the occupational health of workers involved in informal e-waste recycling. Most respondents (80%) reported having no personal protective equipment, with 60% experiencing respiratory symptoms, and 90% stated that they had never received a health check-up in relation to their exposure risks. Blood analyses revealed high concentrations of toxic metals, beyond permissible limits, which are consistent with international data confirming that e-waste exposure is likely to contribute to neurological, respiratory, and reproductive issues (Han et al. 2019). These statistics reflect the insufficient implementation of occupational safety measures and inadequate access to health surveillance among e-waste workers. Previous research has documented similarly dangerous blood lead levels among e-waste handlers, associated with cognitive deficits and organ dysfunction. Therefore, the results support an integrated approach that will comprise the requirement to provide PPE, health surveillance, and educational and training programs, and introduce safe recycling procedures that include mandatory PPE provision, health surveillance, educational and training programs, and the enactment of safe practices in recycling to address both environmental harm and human health (Cui & Zhang 2008).

CONCLUSIONS

This study develops a combined environmental profiling of e-waste recycling in Seelampur, Delhi, India, one of the largest e-waste recycling centers in the country. These findings show that the levels of Pb, Cd, Hg, and Cr in soil and groundwater are often above both the World Health Organization and national allowable guidelines and are greatest in areas with high recycling. Microbial diversity and other indicators of biological contamination, including stressed plants and bioaccumulation in invertebrates, are consistent with these gradients of contamination. Taken together, these results indicate the causality of informal e-waste processing on localized environmental degradation, which relates to the status of ecosystems and possible human contact.

IMPLICATIONS, LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

The combination of abiotic and biotic elements implemented in the current analysis reveals the importance of multi-compartment evaluations in understanding more complex pollution cases. Targeted remediation approaches may be informed by the resulting evidence, and the results could be used to prioritize contamination hotspots to enable regulatory action. To reduce the identified risks, occupational safety standards for recycling workers, increased environmental standard enforcement, and the integration of environmental monitoring into urban waste management policies may be helpful. The procedure adopted herein also provides a guideline that can be applied to other informal recycling centers in India and those in other developing countries in similar situations.

The lack of control or reference sites beyond Seelampur restricts the possibility of attributing all observed contamination to e-waste-related activities only because urban background pollution can also lead to similar outcomes. The biotic indicators based on the partial use of

secondary literature present a form of uncertainty regarding site-specific ecological reactions. In addition, cross-sectional sampling provides only a temporal snapshot and does not account for seasonal or interannual differences in the level of contamination as well as biological effects.

Future studies should include peri-urban or rural control stations to enhance the causal association between sources of contamination. Temporal changes can be detected by longitudinal monitoring over several seasons, which would improve the knowledge of variability in pollutant concentrations and ecological reactions. Increased primary field data assessment of microbial diversity, plant uptake, and invertebrate bioaccumulation would lessen dependency on secondary data and would ultimately deliver more direct evidence of local effects. Integrating environmental measurements with human biomonitoring would also help to provide identified connections between ecological damage and occupational or general health.

REFERENCES

Abalansa, S., El Mahrad, B., Icely, J. and Newton, A., 2021. Electronic waste, an environmental problem exported to developing countries: The good, the bad and the ugly. *Sustainability*, 13(9), pp.5302.

Ádám, B., Göen, T., Scheepers, P.T., Adliene, D., Batinic, B., Budnik, L.T. and Au, W.W., 2021. From inequitable to sustainable e-waste processing for reduction of impact on human health and the environment. *Environmental Research*, 194(3), pp.110728.

Adenuga, A.A., Amos, O.D., Olajide, O.D., Eludoyin, A.O. and Idowu, O.O., 2022. Environmental impact and health risk assessment of potentially toxic metals emanating from different anthropogenic activities related to E-wastes. *Heliyon*, *8*(8).

Ahirwar, R. and Tripathi, A.K., 2021. E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions. *Environmental Nanotechnology, Monitoring & Management*, 15(2), pp.100409.

Akram, S., Najam, R., Rizwani, G.H. and Abbas, S.A., 2015. Determination of heavy metal contents by atomic absorption spectroscopy (AAS) in some medicinal plants from Pakistani and Malaysian origin. *Pakistan Journal of Pharmaceutical Sciences*, 28(5), pp.1781-1787.

Andeobu, L., Wibowo, S. and Grandhi, S., 2023. Environmental and health consequences of e-waste dumping and recycling carried out by selected countries in Asia and Latin America. *Sustainability*, 15(13), pp.10405. [DOI]

Ansari, L., Alam, M.A., Biswas, R. and Idrees, S.M., 2022. Adaptation of Smart Technologies and E-Waste: Risks and Environmental Impact. In: Smart Technologies for Energy and Environmental Sustainability. Springer Publishers, pp.201-220.

Arya, S. and Kumar, S., 2020. E-waste in India at a glance: Current trends, regulations, challenges and management strategies. *Journal of Cleaner Production*, 271(4), pp.122707.

Awasthi, A.K., Awasthi, M.K., Mishra, S., Sarsaiya, S. and Pandey, A.K., 2022. Evaluation of e-waste materials linked potential consequences to environment in India. *Environmental Technology & Innovation*, 28(5), pp.102477.

Awasthi, A.K., Wang, M., Awasthi, M.K., Wang, Z. and Li, J., 2018. Environmental pollution and human body burden from improper recycling of e-waste in China: A short review. *Environmental Pollution*, 243(B), pp.1310-1316.

Awasthi, A.K., Zeng, X. and Li, J., 2016. Comparative examining and analysis of e-waste recycling in typical developing and developed countries. *Procedia Environmental Sciences*, 35(1), pp.676-680.

Azeem, A., Mallawarachchi, H. and Geekiyanage, D., 2019. Building organizational capacities for effective e-waste management: A conceptual framework. *Waste and Circular Society*, 8(2), pp.158-167. [DOI]

Balde, C.P., Kuehr, R., Blumenthal, K., Fondeur Gill, S., Kern, M., Micheli, P., Magpantay, E. and Huisman, J., 2015. *E-Waste Statistics: Guidelines on Classification, Reporting and Indicators*. United Nations University, IAS-SCYCLE, Bonn, Germany, pp.145.

Beula, D. and Sureshkumar, M., 2021. A review on the toxic e-waste killing health and environment – today's global scenario. *Materials Today: Proceedings*, 47(6), pp.2168-2174.

Boubellouta, B. and Kusch-Brandt, S., 2020. Testing the environmental Kuznets curve hypothesis for e-waste in the EU28+2 countries. *Journal of Cleaner Production*, 277(2), pp.123371.

Castro, F.D. and Bassin, J.P., 2022. Electronic waste: Environmental risks and opportunities. In *Hazardous waste management* (pp. 458-421). Elsevier.

Chakraborty, S.C., Qamruzzaman, M., Zaman, M.W.U., Alam, M.M., Hossain, M.D. and Pramanik, B.K., 2022. Metals in e-waste: Occurrence, fate, impacts, and remediation technologies. *Process Safety and Environmental Protection*, 162(4), pp.230-252. [DOI]

Chancerel, P., Meskers, C.E., Hagelüken, C. and Rotter, V.S., 2009. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. *Journal of Industrial Ecology*, 13(5), pp.791-810. [DOI]

Chen, J., Huang, S., BalaMurugan, S. and Tamizharasi, G.S., 2021. Artificial intelligence based e-waste management for environmental planning. *Environmental Impact Assessment Review*, 87(3), pp.106498.

Cui, J. and Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: A review. *Journal of Hazardous Materials*, 158(2), pp.228-256.

Eckhardt, B., 2024. Bridging the knowledge gap! Health outcomes in informal e-waste workers. *Journal of Occupational Medicine and Toxicology*, 19(1), pp.11. [DOI]

Fati, B.M., Ansari, A. and Ansari, A., 2022. Threats of internet-of-thing on environmental sustainability by e-waste. *Sustainability*, 14(16), pp.1-14.

Ferreira-Filipe, D.A., Hursthouse, A., Duarte, A.C., Rocha-Santos, T. and Patrício Silva, A.L., 2025. E-waste plastics in the environment: Assessment, characterisation, and bioprocessing. *Applied Sciences*, 15(4), pp.2122.

Ghulam, S.T. and Abushammala, H., 2023. Challenges and opportunities in the management of electronic waste and its impact on human health and environment. *Sustainability*, 15(3), pp.1837.

Goh, P.G., Maghfouri, M., Onn, C.C. and Loo, S.C., 2022. Life cycle assessment on recycled e-waste concrete. *Case Studies in Construction Materials*, 17(2), pp.e01412.

Gould, P., Song, G. and Zhu, T., 2024. Environmental and economic impact of I/O device obsolescence. *arXiv Preprint Series*, 12(4), pp.2412-20655. [DOI]

Han, Y., Tang, Z., Sun, J., Xing, X., Zhang, M. and Cheng, J., 2019. Heavy metals in soil contaminated through e-waste processing activities in a recycling area: Implications for risk management. *Process Safety and Environmental Protection*, 125(3), pp.189-196. [DOI]

He, Y., Kiehbadroudinezhad, M., Hosseinzadeh-Bandbafha, H., Gupta, V.K., Peng, W., Lam, S.S. and Aghbashlo, M., 2024. Driving sustainable circular economy in electronics: A comprehensive review on environmental life cycle assessment of e-waste recycling. *Environmental Pollution*, 342(2), pp.123081.

Hijazi, O., Okyere, A. and Bernhardt, H., 2021. Environmental Impacts of E-Waste Recycling in Africa. In: Proceedings of the 2021 ASABE Annual International Virtual Meeting. American Society of Agricultural and Biological Engineers, pp.1-10.

Igbo, J.K., Chukwu, L.O., Oyewo, E.O., Blum, J.L., Schanzer, A., Wirgin, I. and Zelikoff, J.T., 2022. The chemistry and health outcomes of electronic waste leachate: Exposure to e-waste is toxic to Atlantic killifish embryos. *Sustainability*, 14(18), pp.11304.

Jain, M., Kumar, D., Chaudhary, J., Kumar, S., Sharma, S. and Verma, A.S., 2023. Review on e-waste management and its impact on the environment and society. *Waste Management Bulletin*, 1(3), pp.34-44.

Kumar, R., Saxena, A., Chawla, J. and Kumar, V., 2024. Environmental Impacts of E-Waste: Pollution and Resource Depletion. In: Sustainable Solutions for E-Waste and Development. IGI Global Scientific Publishing, pp.12-32.

Lee, J., Choi, H. and Kim, J., 2024. Environmental and economic impacts of e-waste recycling: A systematic review. *Chemical Engineering Journal*, 495(2), pp.152917.

Li, W. and Achal, V., 2020. Environmental and health impacts due to e-waste disposal in China – A review. *Science of the Total Environment*, 737(5), pp.139745.

Lin, L., Yang, H. and Xu, X., 2022. Effects of water pollution on human health and disease heterogeneity: a review. *Frontiers in environmental science*, *10*, p.880246.

Liu, K., Tan, Q., Yu, J. and Wang, M., 2023. A global perspective on e-waste recycling. *Circular Economy*, 2(1), pp.100028.

Mishra, K., Siwal, S.S. and Thakur, V.K., 2024. E-waste recycling and utilization: A review of current technologies and future perspectives. *Current Opinion in Green and Sustainable Chemistry*, 45(3), pp.100900.

Mor, R.S., Sangwan, K.S., Singh, S., Singh, A. and Kharub, M., 2021. E-waste management for environmental sustainability: An exploratory study. *Procedia CIRP*, 98(1), pp.193-198.

Novelero, J. and Mariano, O., 2021. Electronic waste management and sustainability practices. *IOP Conference Series: Earth and Environmental Science*, 801(1), pp.012012. [DOI]

Parvez, S.M., Hasan, S.S. and Sly, P.D., 2024. Health risk assessment of humans exposed to soil and dust trace elements from e-waste sites in Bangladesh. *Journal of Environmental Exposure Assessment*, 3(1), pp.27. [DOI]

Parvez, S.M., Jahan, F., Brune, M.N., Gorman, J.F., Rahman, M.J., Carpenter, D. and Sly, P.D., 2021. Health consequences of exposure to e-waste: An updated systematic review. *The Lancet Planetary Health*, 5(12), pp.e905-e920.

Rasheed, R., Rizwan, A., Javed, H., Sharif, F., Yasar, A., Tabinda, A.B. and Su, Y., 2022. Analysis of environmental sustainability of e-waste in developing countries – a case study from Pakistan. *Environmental Science and Pollution Research*, 29(24), pp.36721-36739.

Rautela, R., Arya, S., Vishwakarma, S., Lee, J., Kim, K.H. and Kumar, S., 2021. E-waste management and its effects on the environment and human health. *Science of the Total Environment*, 773(3), pp.145623.

Rawat, S., Verma, L. and Singh, J., 2020. Environmental Hazards and Management of E-Waste. In: Environmental Concerns and Sustainable Development: Biodiversity, Soil and Waste Management. Academic Press, pp.381-398.

Shahabuddin, M., Uddin, M.N., Chowdhury, J.I., Ahmed, S.F., Uddin, M.N., Mofijur, M. and Uddin, M.A., 2023. A review of the recent development, challenges, and opportunities of electronic waste (e-waste). *International Journal of Environmental Science and Technology*, 20(4), pp.4513-4520.

Shi, D.S., Charles, M., Beaucham, C., Walker, S., Alarcon, W., Brueck, S.E., Chiu, S.K. and Somerville, N., 2025. Occupational exposure to mercury at an electronics waste and lamp recycling facility — Ohio, 2023. *MMWR Morbidity and Mortality Weekly Report*, 74(1), pp.9-13.

Silva, J.A.P., Lima, G.G., Camilo-Cotrim, C.F., Bailão, E.F.L.C., Caramori, S.S., Nabout, J.C. and Almeida, L.M., 2023. Impact of e-waste toxicity on health and nature: Trends, biases, and future directions. *Water, Air, & Soil Pollution*, 234(5), pp.320.

Singh, N. and Ogunseitan, O.A., 2023. Climate change implications of electronic waste: Strategies for sustainable management. *Bulletin of the National Research Centre*, 47(4), pp.1124. [DOI]

Singh, Y., 2025. *E-Waste Management*. Academic Research Press, New Delhi, pp.210.

Thakur, P. and Kumar, S., 2022. Evaluation of e-waste status, management strategies, and legislations. *International Journal of Environmental Science and Technology*, 19(7), pp.6957-6966.

Vats, M. and Singh, S., 2014. E-waste characteristic and its disposal. *International Journal of Ecological Science and Environmental Engineering*, 1(2), pp.49-61.

Yu, Z., Tian, X., Gao, Y., Yuan, X., Xu, Z. and Zhang, L., 2023. Monitoring the resources and environmental impacts from the precise disassembly of e-waste in China. *Environmental Science & Technology*, 57(22), pp.8256-8268.

Zhao, L., Zhou, F., Wang, S., Yang, Y., Chen, H., Ma, X. and Liu, X., 2024. Bisphenol chemicals in surface soil from e-waste dismantling facilities and the surrounding areas: Spatial distribution and health risk. *Toxics*, 12(6), pp.379. [DOI]