Environmental impact of e-waste management in Indian microscale informal sectors

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Abstract

Inappropriate e-waste processing in the informal sector is a serious issue in developing countries. Field investigations in microscale informal recycling sites have been performed to study the impact of hazardous metal(loid)s (released from e-waste dismantling) on the environment (water and soil). Eight hazardous metal(loid)s (Pb, Cd, Cu, Zn, As, Hg, Ni, and Cr) were primarily found in the monitored water and soil samples (Sangrampur, West Bengal) because of widespread informal e-waste handling and primitive processing. Elevated concentrations of Cd, Pb, As, Cu, and Cr were observed in pond water samples (0.04, 1.62, 0.03, 1.40, 1.74 mg/L respectively). These ponds, which are regularly used for e-waste handling/dismantling, are usually flooded during the monsoon season mixing with further larger water resources — posing a serious threat to public health. Enriched levels of Pb, Cd, Cu, and Zn were detected in collected soil samples, both top surface soil (Pb up to 2042.27 ± 206.80, Cd up to 25.90 ± 9.53, Cu up to 6967.30 ± 711.70, and Zn up to 657.10 ± 67.05 mg/Kg) and deeper subsurface soil (Pb, 419.70 ± 44.70; Cd, 18.34 ± 3.81; Cu, 3928.60 ± 356.40; and Zn, 134.40 ± 33.40 mg/Kg), compared to the levels of As, Hg, Ni, and Cr. Seasonal variation of soil metal(loid) content indicated that higher levels of most of the metal(loids) were detected in the pre-monsoon (Nov–May) season, possibly due to the monsoonal dilution effect, except for Pb and Cd. The results highlighted that the composition and the handling of e-waste were important factors affecting the metal(loid) concentrations. E-waste policy and legislation have great influence on the handling and disposal procedures. An improved e-waste management practice has been proposed to encourage eco-friendly and safe e-waste disposal. It is recommended that regulatory agencies and manufacturers should create a road map to convince the informal sector to develop a systematic approach towards a more standardized formal e-waste management practices at the microscale field level.

Introduction

The disposal of electrical and electronic equipment (EEE) is an increasing global challenge due to the rapid obsolescence of technology, shorter lifespan of devices, and inappropriate recycling and reuse of e-waste in the informal sectors (Balde et al. 2015; Awasthi et al. 2016, 2022; Dasgupta et al. 2017; Saha et al. 2021). Globally, the generation of e-waste was 53.6 MT in 2019 and projected to grow to 74.7 Mt by 2030 (Forti et al. 2020). The growth of e-waste has been exponentially expanding especially over the last two decades (Dasgupta et al. 2014; Purchase et al. 2020). The e-waste generation growth rate (both globally and regionally) clearly indicates that the existing management protocol of e-waste is complex and multifaceted that needs serious policy attention.

In Europe, recently (2018) legislated streamlining activities (building systems to reuse and recycle old EEEs) are focused on ensuring a better mechanism for handling and disposal of e-waste. Poorly working and easily disposable EEE items are the principal source of e-waste at the end of their lifespan (Purchase et al. 2020). These items include personal computers, laptops, televisions, mobile phones, and household gadgets — most often discarded by the users. Consequently, the per capita e-waste generation is increasing, and the generation of e-waste leads to an increase in the handling and disposal problems with a high ecological impact (Dasgupta et al. 2014). According to the global e-waste monitor (Forti et al. 2020), Europe has the highest collection and recycling rate (42.5%), followed by Asia (11.7%), Americas (9.4%), and Oceania (8.8%). The African continent has the lowest rate at 0.9%. In high-income countries, most of the e-waste is recycled formally whereas, in middle and low-income countries, e-waste is handled mainly by the informal sector.

Developed countries have strict laws and protocols to tackle huge volume of e-waste. In contrast, legislations are implemented in a very relaxed manner and most of the generated e-waste is handled in the informal sector in developing countries (Ongondo et al. 2011; Garlapati 2016). The informal sector has a lucrative business model. Because e-waste open burning is a secondary source of precious and valuable metals which gives quick earning opportunity, extended source of income, and better livelihood. These are mostly operated from the outskirts of megacities (Secretariat Report 2007; Nandi 2010; Secretariat Report 2011; Awasthi et al. 2022). A large section of the population in the developing countries buys products from second-hand markets (SHM) due to economic constraint (Dasgupta et al. 2017). The products from the SHM are used by the consumers after necessary refurbishment. These SHMs then contribute to the mushrooming growth due to easy microscale operation in

the backyard of the rural outskirts by the low-income groups and traded informally by the scrap-dealers often by local trains. They handle approximately 90% of the total generated e-waste in developing countries and are vital to the livelihood of the engaged human workforce (Young 2004; Satyamurty 2006; Toxic Link India 2007; Hulladek 2021).

Among the developing countries, India is a renowned "hot spot" of e-waste generation as well as a dumping destination (Purchase 2020). In India, ten techno-commercial cities contribute to nearly 70% of total e-waste generated (Toxic Link India 2007; Secretariat Report 2011, 2021). The major primary sources of e-waste in India (70%) are governmental (15%), public (23%), and private (32%) sectors followed by household contributors (15%) (Satyamurty 2006; Secretariat Report 2010; CPCB 2021). E-waste generation is complex because reuse, storage, and recycling are always practiced before final landfilling (Dwivedy and Mittal 2010). Among these, the reuse practice is principally dependent on the market demand of the product (reselling). The large quantities of e-waste that are eventually dumped at the recycling sites have the potential to release/emit substantial number of contaminants/pollutants in soil and water environment (Dasgupta et al. 2015; Purchase et al. 2020; Saha et al. 2021).

E-waste recycling/recovery operations and open burning activities release several hazardous substances. These are mostly toxic metal(loid)s and organic compounds (e.g., flame retardants) that are detrimental to environment and public health (Dasgupta et al. 2015; Guha Thakurata 2015). Studies suggest that recyclers/handlers/waste workers (primarily children and women) are largely affected by the exposure of inorganic/organic substances derived from e-waste processing in India, including Kolkata and the surrounding areas (Chen et al. 2011; Guha Thakurata 2015). The "microscale" e-waste processing is done by small group of people (10–20 heads) and mostly dominated by women and children. The operation is largely dependent on e-waste supply chain amounting up to 3 MT/year (Dasgupta et al. 2014, 2017). Existing policies are made for macroscale management of e-waste (Rigoldi et al. 2018). However, inappropriate e-waste handling leads to their unrestrained disposal which may cause serious impact on water, soil, and human health (Dasgupta et al. 2015; Purchase et al. 2020). This needs future policy amendments to bridge up knowledge and policy gaps mainly at local microscale level.

This study focuses on hazardous metal(loid) pollution from microscale informal sector e-waste processing sites in rural India, which is underexplored in the Indian sub-continent. A comprehensive field scale study has been conducted to demonstrate the

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enrichment of hazardous metal(loid)s in water and soil environment. The seasonal variation of these toxic metal(loid)s is studied to investigate the relationship between their mobilization and microscale e-waste processing. Moreover, the study also critically examines the link between microscale informal trade chain practices and their consequence on final disposal, its ecological impact, and management policies. Finally, an appropriate management skill model has been developed to resolve the challenges in entire south-east Asia to regularize e-waste processing in rural microscale informal sectors.

Methods and materials

Study area

The study area (Fig. 1), near Sangrampur (22º12′4.7″–22º14′8.0″N and 88º18′58″–88º22′57″E, South 24 Parganas, West Bengal), is 75 km away from Kolkata Metropolis and falls within the "tropical wet and dry" category (Dasgupta et al. 2015, 2017). The daily maximum temperature hovers around the 30–40 ºC in summer and winter 10–20 ºC. The average annual rainfall is about 1750 mm (Dasgupta et al. 2015, 2017). Four different sites have been selected for the study, namely — Teckpanja (Site 1), Bankipur (Site 2), Talpadmer Hat (Site 3), and Jhapberia (Site 4). Nishapur was selected as the "control site" having no history of e-waste handling. The field visit revealed that informal recycling activities are being practised in site 1, 2, 3, and 4 for nearly three decades (1994). The soil texture of all the sites (area up to 524 sq. ft) appeared to be burnt, tarnish, and completely black in color (Supplementary Fig. S1a–b). During field expeditions, these e-waste burning sites were found to be low and flat, rich in fresh organic matter due to the decomposition of animal wastes and were often used for cattle grazing.

E-waste items are often refurbished, and useable electronic items are sold to the SHMs/scrap dealers which are commonly regulated by trade chain practices (Fig. 2). The recovered components are sold for recycling purposes along with local market. Several kinds of e-waste are processed in those monitored recycling sites. The major items are printed circuit boards (PCB), power cables, cathode ray tubes (CRT), lead containing solders, plastic housing, and nickel–cadmium batteries (Supplementary Fig. S2). In the dismantling operation, the equipment used is mostly primitive in nature and rudimentary in type (hammer, chisels, hand-driven driller). However, the methods of operation are highly non-standardized being labor-intensive and without any energy sources. Dismantling (e.g., PCB) is done by hammering to recover metals and the dismantled e-items are regularly washed into the nearby

ponds. Several plastic-coated e-items are open-burned to recover the metals from inside. The burning activity takes place 2–4 times a week (Dasgupta et al. 2015, 2017).
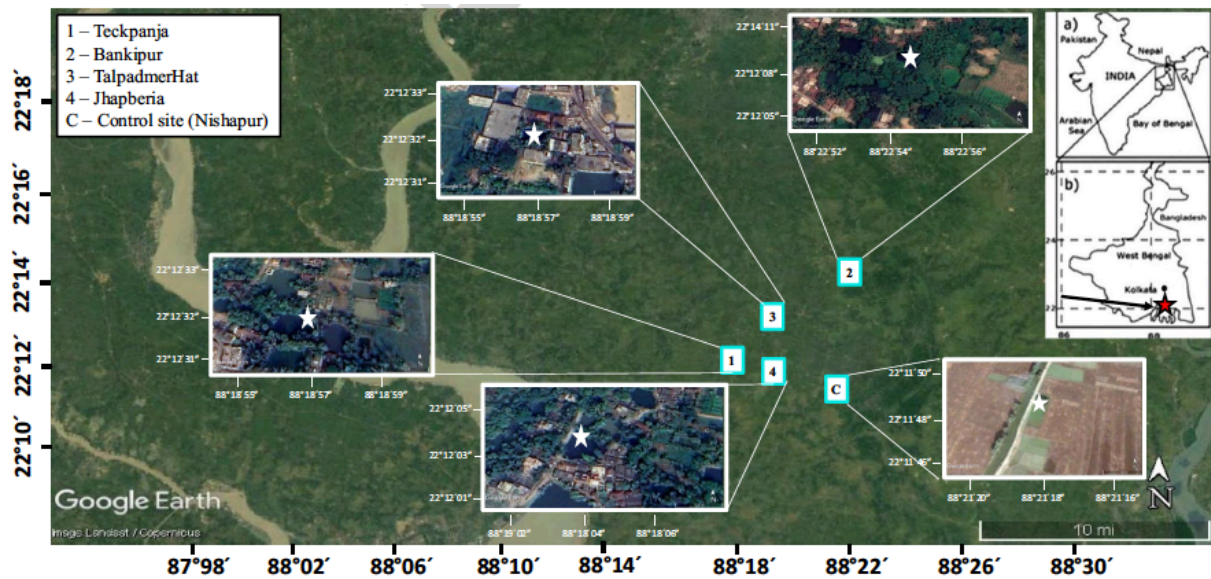

Fig. 1 Study area (Sangrampur, West Bengal) with pond locations shown as white stars within each of the sites. The image is downloaded from Google Earth.
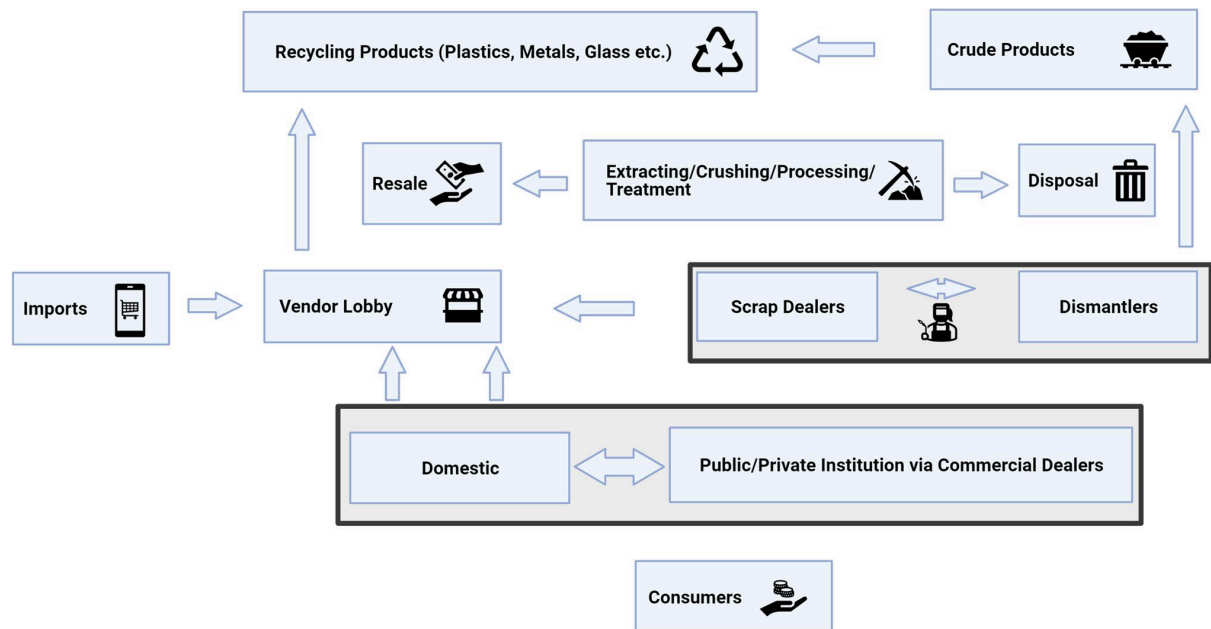

Fig. 2 The trade chain of the e-waste handling practices

Sample collection and preparation

Soil

The sampling campaign (composite and representative soil sampling) has been conducted for pre-monsoon (Pre M, April 2017) and post-monsoon (Post M, October 2017) seasons. Vertical depth-wise (0–15, and 15–45 cm below ground level (bgl)) composite samples were collected from the monitored four sites and the control site. Collected samples were air-dried and manually homogenized. Each air-dried sample was then transferred to a stainless-steel sieve (< 2 mm), which was then covered with a steel lid and shaken manually. The sieved samples were stored and transported to the laboratory on the day of sampling and kept at 4 ± 1 ºC.

Water

Water samples (grab) were collected from four different ponds that were used for waste washing (at 20 cm below the surface, Fig. 1 and Supplementary Fig. S3). One pond from each study site was sampled, located in the vicinity of e-waste open-burning sites (2–5 m) during Pre M and Post M season. Samples were collected in pre-acid cleaned PET bottles (100 mL); they were acidified (2% v/v) with HNO_3 (ultrapure, Merck) and stored in icebox (4 ± 1 º C). Then they are transported to the laboratory on the day of sampling and kept at 4 ± 1 º C till the analysis.

Analysis of metals, organic matter and pH

Concentrations of Pb, Cd, Cu, Zn, Ni, and As in the soil and water samples were determined. For hazardous metal screening, soil samples were extracted by the method used in Fujimori et al. (2012). In short, collected soil samples (1 g) were pre-digested overnight in conical flask with equal volumes (3 mL) of different mixtures of acids (HNO_3 60% + HCl 35% ultrapure, Merck) with deionized water (25 mL). The overnight acid-soaked samples in a conical flask covered with a watch glass are then heated on a hotplate (up to 125 ± 5 ºC) for 2 h and the watch glass was removed. The samples were further heated for nearly 10–15 min until the total volume was reduced to 15 mL and cooled down to room temperature. They were filtered (0.45μ, Sartorious, Germany) and the volumes were made up to 50 mL in a flask. The water samples were filtered (0.25μ, Sartorious, Germany) to remove any tiny, suspended particulates. The filtered samples (50 mL) were then acidified (conc. HNO_3 2.5 mL, ultrapure, Merck) and digested on a hotplate. Digestion continued until a clear solution was obtained. The solutions were cooled down to room temperature and then transferred to a

volumetric flask and made up to 100 ml (Fujimori et al. 2012; Maris et al. 2015; Vazquez and Barbosa 2017). The acidified water samples were filtered (0.45, Sartorius, Germany) before elemental analysis was carried out.

The hazardous metals in the acid extracted soil samples and water samples were measured by atomic absorption (Varian AA 240; Hg in cold vapor, As in hydride generation mode) as per a standard method (Baird et al. 2017). Twenty percent of the samples were selected randomly to test the precision of the analysis (> 97%, p < 0.01). Certified reference materials (NIST SRM 2709a, SEM 1643e) were used to maintain the accuracy of the analysis. For soil pH measurement, samples were first air-dried, ground into powder, and passed through a 2 mm sieve. Only the soil < 2 mm was then mixed with distilled water (1:2.5, w/v) for 30 min and the pH of the mixture was measured using a multimeter (WTW, Germany) (Wu et al. 2015). Soil organic matter (OM) was measured using a modified dichromate oxidation method (Meersmans et al. 2009).

Paired t-test was carried out for statistical significance by using SigmaPlot version 14.5 (Systat Software Inc., USA) to compare the significance of the analyzed metal(loid) concentrations for Pre M vs. Post M of the four sites, and also, Pre M-Post M metal(loid) concentrations from the four sites vs. Pre M-Post M metal(loid) concentrations from the control site.

Results and discussion

Pond water contamination

The levels of hazardous metal(loid)s in the monitored pond water samples are summarized (Fig. 3a–d and also available in Supplementary Table S4). Absolute metal(loid) concentrations from all the sites (both Pre M and Post M) are presented in the figures, whereas the supplementary table depicts the respective national (BIS 2012) and WHO guideline (WHO 2008) values as well. The overall concentrations of almost all the metal(loid)s are found to be higher during the Pre M season in comparison to the Post M season (except Hg). Results indicate that Cd levels are relatively higher, almost in all the sites with regard to both the national and WHO guideline values, especially during the pre-monsoon seasons. The concentrations of Pb, Cu, and Cr have shown similar trends. The monitored pond water in the vicinity of e-waste opens burning sites appeared to be affected by hazardous influence from certain toxic metals. In particular, Cd, Pb, Cu, and Cr seemed to have leached out from burnt e-waste residues into the pond waters. Studies (Saha et al. 2021

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and the references therein) have shown that leachate from e-waste landfill sites could act as a potential hazardous resource for toxic metal(loid) mobilization in the ambient environment. The overall absolute concentrations of Zn and Ni in all the samples apparently seems to be on the higher side in comparison to many of the other metal(loid)s (Fig. 4a–d); however, they both remain under their respective national (Zn, 5 mg/L and Ni, 0.02 mg/L) as well as WHO guideline (Ni, 0.07 mg/L) values.
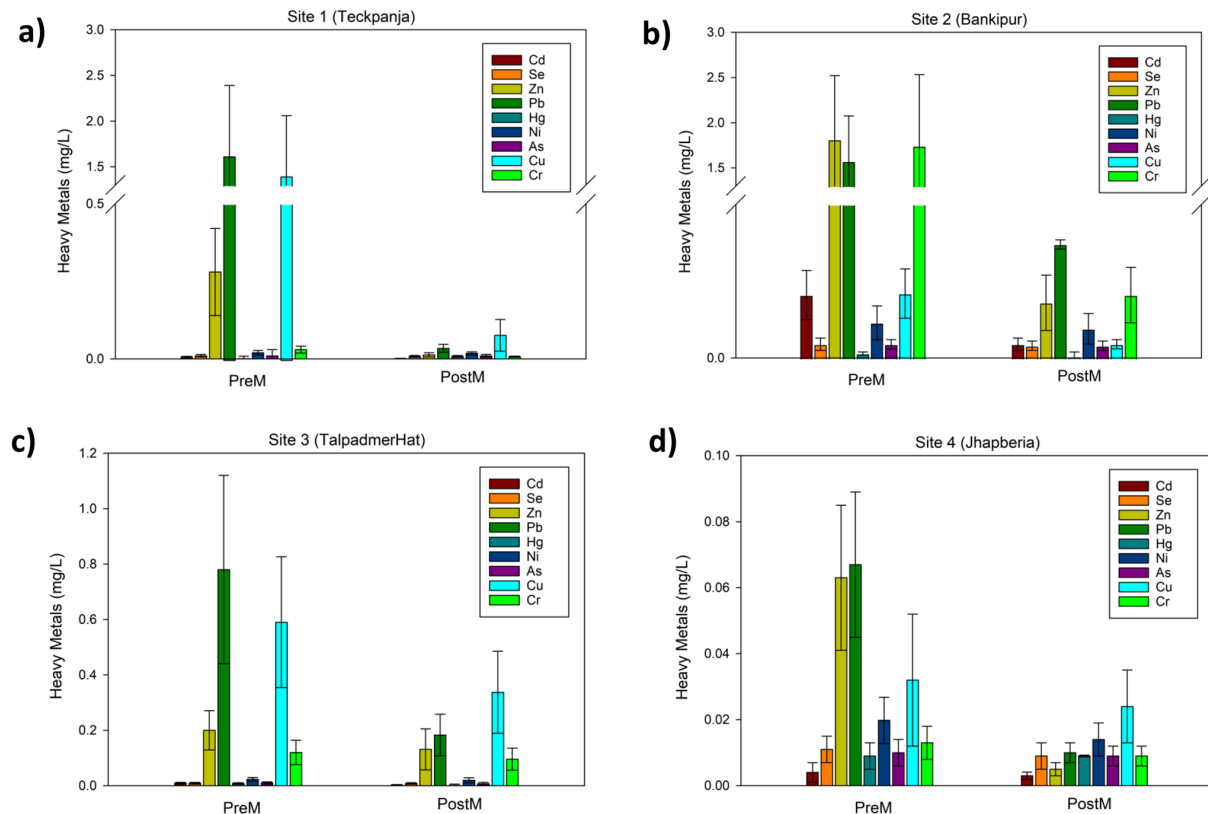

Fig. 3 Metal(loid) distribution in pond waters from different sites

Spatial and temporal variations of hazardous metal(loid)s across the study sites are also observed (Fig. 3a–d and Supplementary Table S4). The levels of Cd, Pb, Cu, and Cr in Pre M season are higher than the permissible limit for safe water (National as well as WHO standards). However, in case of Cd, the concentrations go down below the acceptable limits during the Post M season in all the sites, except site 2. Another highly toxic element As shows higher concentration in site 1, but only during the Pre M season. The study indicates the presence of hazardous metal(loid)s in all monitored pond waters, often used for drinking purposes, located in the vicinity of the open burning sites. However, the levels are varied both spatially and temporally. The metal(loids) become serious environmental concern whenever

they exceed the National drinking water standard as well as the WHO guideline values recommended for human health safety (WHO 2008; BIS 2012).
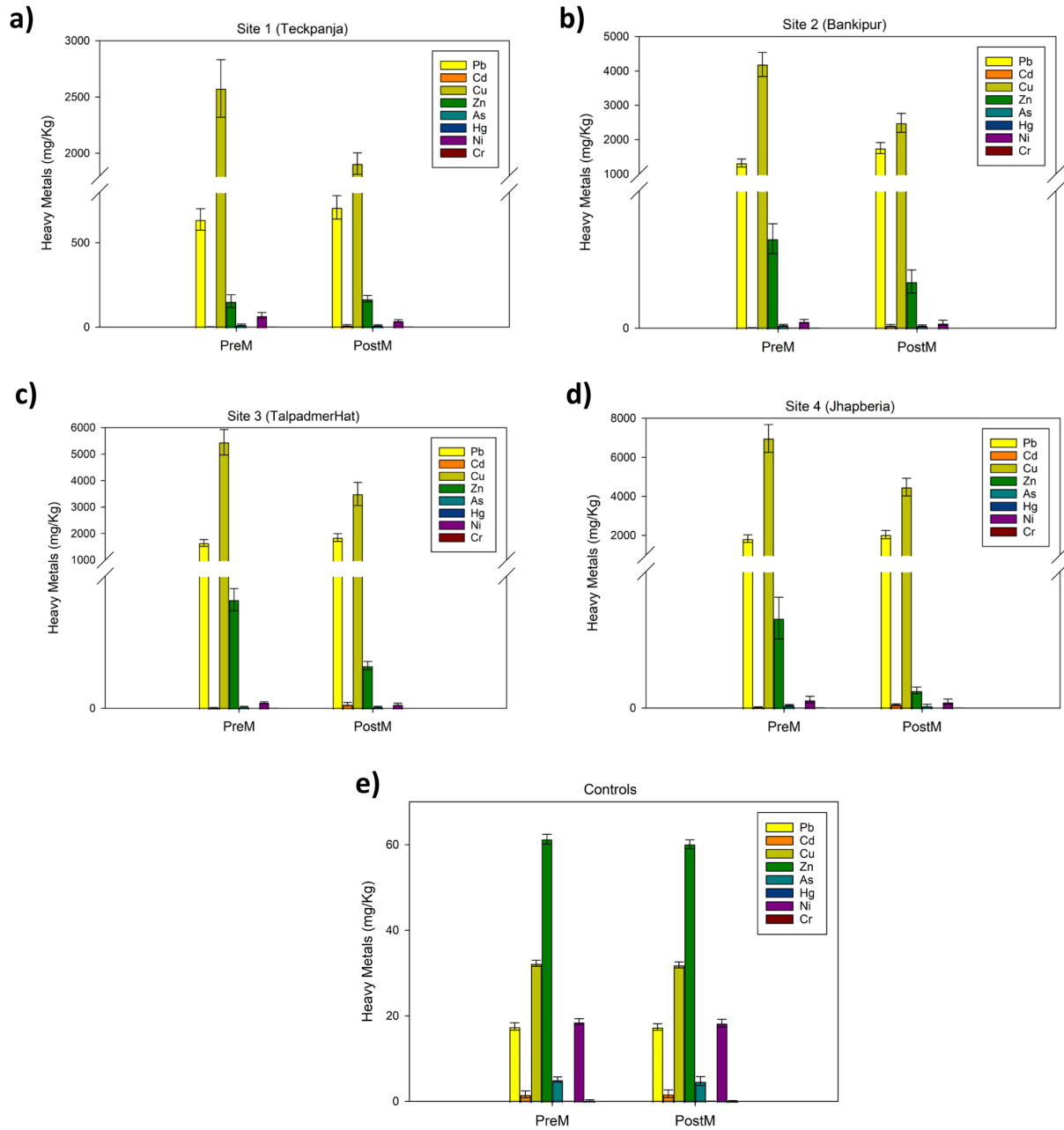

Fig. 4 Metal(loid) distribution in surface soil samples (0–15 cm, bgl) from different sites. a site 1, b site 2, c site 3, d site 4, e control site

These frequently found metal(loid) concentrations indicate the regular use of pond water to wash the burnt e-waste residues (Supplementary Fig. S3), primarily from PCB, smart card chips, CRT containing CdS, photovoltaic panels, capacitors, and batteries — which are commonly found in the disposed e-waste. Similarly, Hg is probably leaching out from LCDs and/or batteries that are widespread and regularly burnt (Schlummer et al. 2007; Dimitrakakis et al. 2009; Erickson and Kaley 2011). Seasonal variation is always an important issue with regard to the monitored pond water. A distinct feature is the higher levels of all the hazardous metal(loid)s in Pre M season compared to Post M. The Post M levels are mostly within the safer limits. As in many cases, the rural agricultural practice involves pond waters for irrigation. Hence, using pond waters with high concentrations of toxic metal(loid)s in these areas pose a threat to the wider ecological health and safety concerns through contamination of agricultural crops (Wu et al. 2015). This advocates for specific policy establishment for purification of pond waters, with special focus on seasonal variation as observed in this study.

The seasonal variation can be explained by the monsoonal dilution effect, thereby resulting in lower concentrations of toxic metal(loid)s, Post M. The often-found higher concentrations of Cd, Pb, Cu, and Cr reflect the frequent use of pond water to wash the burnt residues; thereby, metals are released to aqueous environment (Wu et al. 2015). This is due to recovery of hazardous metal(loid)s (Cd, Pb, Zn, Cr, As, Hg) that are usually done by acid stripping with strong oxidizing acids (crude commercial grade), where aqueous pH is decreased causing the metal(loid)s to be quite soluble in water (Sthiannopkao and Wong 2013).

Soil contamination

The levels of hazardous metal(loid)s (Pb, Cd, Cu, Zn, As, Hg, Ni, and Cr) were studied in vertical soil distribution (0–15 cm, bgl (Fig. 4a–e) and 15–45 cm, bgl (Figs. 5a–e)) sampled from open burning sites. The results are also presented in tabular form (also available in Supplementary Tables S5, S6, S7, S8, and S9) to compare the values with the USEPA limits for the respective metal(loid)s in soil. Briefly, the soil load of the hazardous metal(loid)s is much higher when compared to the control site (Nishapur, nearby non-contaminated agricultural land) (Figs. 4e, 5e, and Table S9).

The levels of Pb, Cu, and Zn in soil samples collected (0–15 cm, bgl) from all the sites often exceeded the Indian National Standard for soil (Pb: 250–500 mg/Kg, Cu: 135–270 mg/Kg, Zn: 100–200 mg/Kg) (IS-2000). Moreover, Pb and Cu levels also exceeded the USEPA standard in all the samples, be it the surface soil or the deeper soil (USEPA 2012) (Fig. 4a–e,

Fig. 5a–e, and Supplementary Tables S5, S6, S7, and S8). Across all the study sites, Cd seems to exceed the USEPA limit during the Post M season. The concentrations of Zn in sites 2, 3 and 4, on the other hand, visibly show higher concentrations (> USEPA value) for the surface soils. The deeper soils from those three sites, as well as site 1 in general, are apparently showing safer concentrations in terms of soil Zn concentrations. Similarly, As, Hg, Ni, and Cr generally remain below the USEPA standard (Abbasi et al. 2016). The result shows that the predominant soil metals are Pb, Cd, Cu, and Zn as they also tend to exceed the respective USEPA guidelines. The study further reveals that the overall concentrations of the metal(loid)s decrease from Pre M to Post M season, except for Pb and Cd (Fig. 5a–e and Supplementary Tables S5, S6, S7, and S8) (Fergusson 1990). Field observations revealed that open burning of power cables has been done regularly to recover Pb, Cu, and Zn which ultimately resulted in overall contamination of the soil. Additionally, acid stripping was noted to be a common process for recovery. These released acid wastes directly to the soil environment. Thus, the comparison of results highlights the close relationship between the recycling work performed at the e-waste handling sites and the alarming accumulation of the elevated metal(loid)s in soil (Wu et al. 2015).

Both the results (water and soil) showed variations in the levels of hazardous metals (Pb, Cd, Cu, Zn, As, Hg, Ni, and Cr) in between monitored sites that are linked with the type of e-waste openly burned. A quick p-test (Supplementary Table S10) on soil metal(loid)s from all the sites shows that the decrease in metal(loid) concentrations (from Pre M to Post M) are not significant ($p > 0.001$) for the surface soils (0–15 cm). However, the reduction in concentrations is significant ($p < 0.001$) for the deeper soil (13–45 cm) region. On the other hand, in the case of all four sites, the increased concentration of metal(loid)s, in comparison to the control site, is significant ($p < 0.001$) in deeper soil region for both seasons. However, the concentration increase is only significant during the Post M season in the case of the surface soils (Supplementary Table S10). This indicates a dynamic and faster dilution of surface soil metal(loid)s possibly through monsoon rain-driven surface runoff as the change is more significant during the Post M season and not during the dry Pre M season. However, in the case of the deeper soil region, the metal(loid) mobilization seems to be more geochemically controlled and hence more stable. The e-wastes involved are primarily PCB, CRT displays, power cables and plastics. They were dismantled manually followed by acid bathing in recycling sites. These factors may have catalytic effects on hazardous metal(loid) concentrations in soils and waters (Uchida et al. 2018).

Results suggested that Pb, Cd, Cu, and Zn have contaminated the soil environment at a considerable level (Fig. 4a–e, Fig. 5a–e, and Supplementary Tables S5, S6, S7, and S8). An increase in mobility is possible alongside the increase in soil contamination with the enhanced levels of Pb, Cd, Cu, and Zn (Fijałkowski et al. 2012). The downward movement of these hazardous metals is seemingly inhibited from the surface soil to the deeper soil, both in Pre M and Post M season (Supplementary Table S5, S6, S7, and S8). However, even only a varying fraction of surface soil content, the downward movement could be facilitated by water soluble forms of the respective metal(loid)s (Ceballos and Dong 2016; Zhang et al. 2019). In this context, Cd is highly mobile in the soil–plant system and associated with high bioavailability and risk (Xing et al. 2009; Kumar and Rawat 2013). Pb may impose a moderate risk to water, soil, and food chain whereas Cu may pose low risk both in terms of bioavailability and low uptake in food chain (Moral et al. 2005). As, Hg, Ni, and Cr were relatively more restricted compared to Pb, Cd, Cu, and Zn in downward movements. The mobility of these hazardous metal(loid)s was limited possibly due to adsorption by clays (Alloway 1995).

The monsoonal impacts on the changes in metal(loid) levels are examined. Result reveals that during the Pre M season (dry, Nov–May), these hazardous metal(loid)s had elevated levels as open dumping and burning of e-waste are a common practice. However, Pb, Cd and occasionally Cu were found to be elevated in Post M season. The results highlighted that the origin of the handled e-waste in those monitored sites along with the process of open burning influenced the level of the metal(loid) present in the soil and water environment. The earlier studies in SE Asia also revealed that toxic and hazardous metals regularly emitted from e-waste informal recycling centers. Those studies demonstrated pollution in the air, water, and soil environment, and also plants and human uptake (Table 1).

During the monsoon season, inundation due to continuous flooding increased soil pH while redox potential (E_h) decreased over time (Vaněk et al. 2005; Oluyemi et al. 2008). The prolonged water-logged condition results in enriched Pb, Cd, Cu, and Zn levels in pore water, where controlling factors are pH, E_h, presence of Fe, dissolved organic matter, and the presence of oxy-anions (Vaněk et al. 2005). Consequently, a gradual migration of more labile forms of these hazardous metals (in this case Pb, Cd, Cu, and Zn) and their intensive accumulation could result in their downward movement, notably in the Post M season (Pan et al. 2021). In this regard, metal chemical forms (mostly water soluble) and their higher mobility were majorly responsible for transfer to soil environment (Pan et al. 2021), and

dependent on their chemical nature, mobility coefficient, enrich levels, and favorable soil environment (Pan et al. 2021).
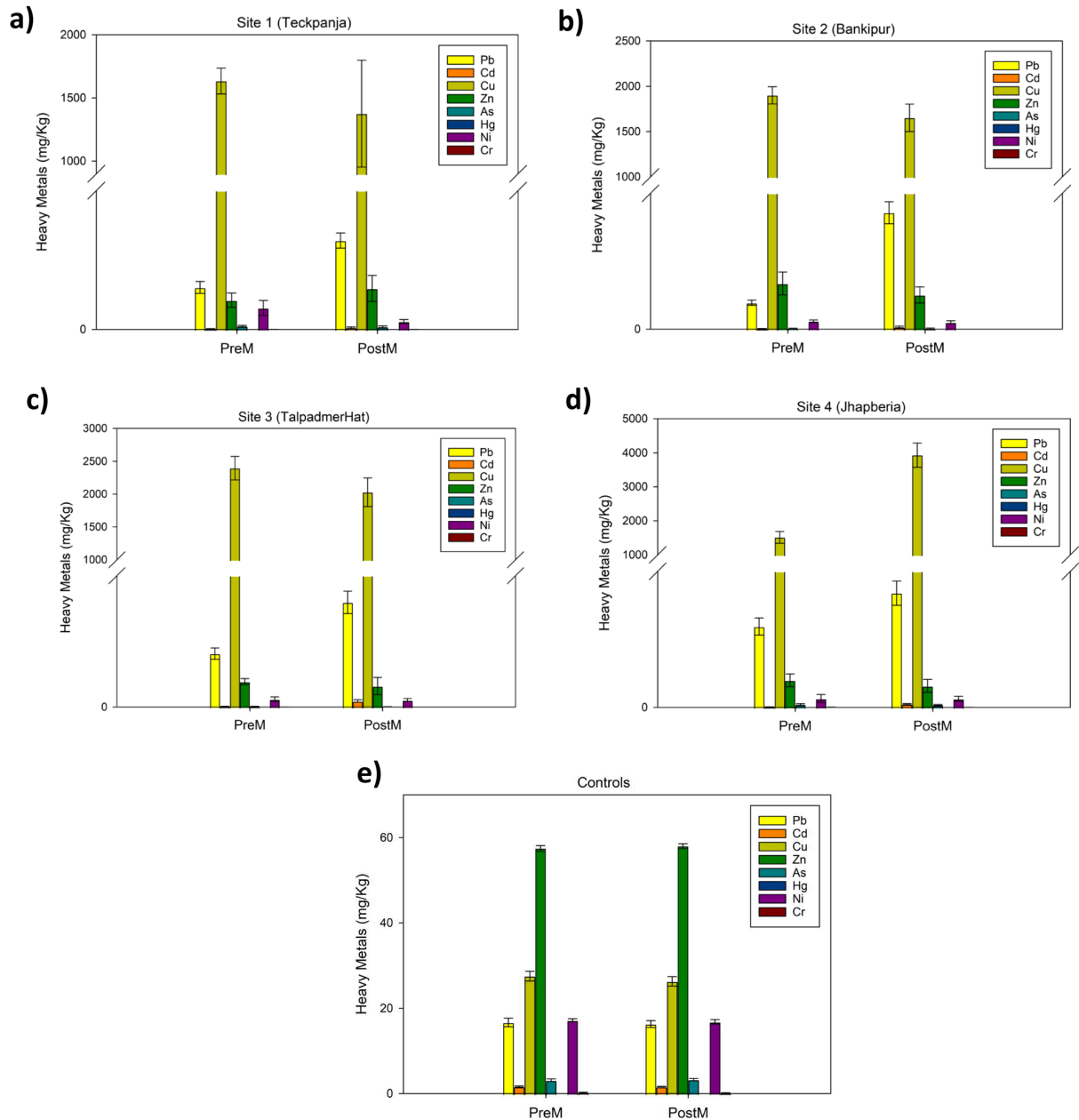

Fig. 5 Metal(loid) distribution in deeper subsoil samples (15–45 cm, bgl) from different sites. a site 1, b site 2, c site 3, d site 4, e control site

It was observed that the concentrations of heavy metals are much higher in the surface soil than the deeper soil due to anthropogenic activities (Dasgupta 2016; Isimekhai et al.

2017). It was observed that after rainy days, dismantling activities intensify. Approximately 30–40 kg of e-wastes is dismantled in 3–4 days around that time. The obsolete e-items (e.g., CRT) are the major sources of Pb, Cd, Cu, and Zn and are attributed to the elevated concentration of these four elements in the soil samples. Other variations were due to the different nature of the e-waste being handled.

Table 1 Scenario of environmental contamination from different E-waste informal sites in southeast Asia. PBDE, polybrominated diphenyl ethers; PCB, polychlorinated biphenyls; PCDD/F, polychlorinated dibenzo-p-dioxins and dibenzofurans.

Country	Environmental issue/concern	Nature of handling/disposal	Nature of contaminants	Exposure levels	References
China and Hong Kong	Atmospheric pollution	Recycling Centre	Upto 2765 pg/m^3	PBDEs	Li et al. (2006)
China	Soil-plant - crop	Recycling site	NA	PBDEs, PCBs and PCDD/Fs	Liu et al. (2008)
China	Soil-Plant-Crop (Human uptake via rice)	Agricultural field adjacent to recycling site	3.7/0.7 µg/day/kg (dry wt.)	Heavy metal Pb & Cd	Fu et al. (2008)
China	Human (child blood sample)	Exposure to worker in recycling site	10µg/dl	Cd	Zheng et al. (2008)
India	Soil – (ground) Water environment	Recycling site	NA	Heavy metals (Cu, Al, Pb, Zn, Ni, Mn and Cd)	Dwivedy et al. (2015) Gidarakos et al. (2012)
India	Soil- (surface) Water environment	Recycling site (outskirts of megacities)	Pb(637.8±63.70) Cu(2576±235.80) As (14.69±4.08) Hg (0.05±0.01)	Heavy metals (Cd ,Se , Zn ,Pb, Ni, As, Cu, Cr)	Dasgupta et al. (2017)
Vietnam	Human (THs ,Thyroid hormones)	Recycling site	NA	PCBs, hydroxylated PCBs (OH-PCBs), PBDEs,	Hischier et al. (2005) Eguchi et al. (2015)

The interesting part of the study is the internal spatial variability of metal(loid) concentrations between the study sites in water and soil environ (Figs. 3a–d, 4a–e, and 5a–e). The monitored variation is due to difference in e-waste handling and operation as well as the site-specific environmental conditions and influencing factors (Dasgupta 2016; Saha et al. 2021). In site 1, all the hazardous metal(loid)s are relatively low in water due to lesser

handling activity in comparison to the other three sites. The remaining three sites are, in fact, closer to the nearby railway station, thereby catalyzing quicker transportation of e-wastes. Similarly, the variability in soil metal(loid) concentrations among the monitored sites may also be explained based on the different scale of handling and operation among these sites.

The study indicates hazardous metal(loid) mobility in environment and showing distinct distribution pattern between surface soil (0–15 cm) and deeper subsoils (15–45 cm). Soil organic matter and pH are two important factors to influence the mobility of hazardous metals (Cu, Cd, Pb, As). The organic matter content of the soil environment (Figs. 6a–b and 7a–b) has been found to be higher in concentration when compared to the control site. The relatively higher organic matter expedites the redox driven mobility of metal(oid)s increasing the metal(loid) contents in the soil environment, notably in surface soil (Covelo et al.2007; Jiang et al. 2019). On the other hand, the more acidic pH increases the solubility of metal(loid)s and thereby the mobility of hazardous metals in environment. As a result, hazardous metal(loid)s (e.g., Pb, Cd, Cu, Zn, and also As in some cases)) are increasing in the soil environment in all the monitored sites. The seasonal variation of the monitored sites is also important because the speciated forms are existing due to reducing conditions and thereby largely contributing to their mobility (Luo et al. 2011; Sungur et al. 2014; Jiang et al. 2019). However, the mobility mostly depends on their chemical nature and redox pattern in different ecosystems (Boteva et al. 2015; P.rez-de-Mora et al. 2006; Jiang et al. 2019). As can be seen here (Figs. 7a–b, 8a–b, and also available in Supplementary Table S5, S6, S7, and S8), most of the soil metal(loid)s are found in elevated concentrations during the Pre M season in comparison to the Post M season (dilution effect). However, Pb and Cd show an opposite trend when their concentration increases on going from the Pre M to Post M season. This could be due to their tendency to form less labile, mobilizable species (and hence tend to remain adsorbed to the host soil) under more reducing conditions with high organic matter load, more negative Eh, and more acidic pH. Additionally, metal(loid)-reducing bacteria may also facilitate the soil absorbed hazardous metal(loid)s, resulting in their solubility in soil environment (Francis and Dodge 1990; Zachara et al. 2001; Jiang et al. 2019). These aspects need further and focused investigation.
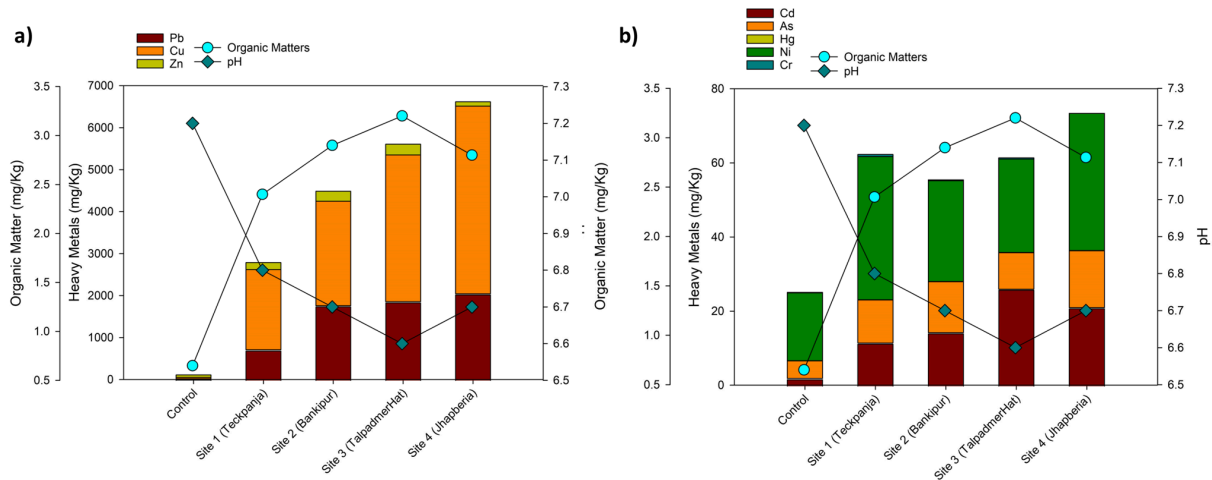
Fig. 6 Relationship between soil (0–15 cm, bgl) metal(loid) concentrations with soil organic matter and pH
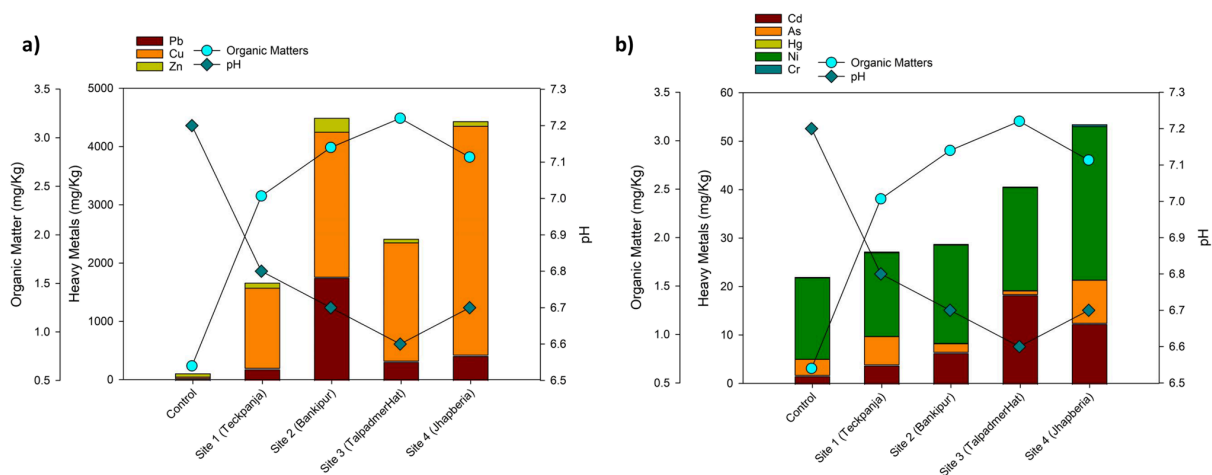

Fig. 7 Relationship between soil (15–45 cm, bgl) metal(loid) concentrations with soil organic matter and pH

The present study (across traditional e-waste sites) has demonstrated an important source of hazardous metal (Pb, Cd, Cu, and Zn) pollution in water and soil environment due to microscale e-waste operational activity. The potential ecological risk notably to human, animal, and agriculture from all the four sites is dominated by Pb, Cd, Cu, and Zn poisoning (He et al. 2017). Therefore, immediate policy regulation with focused vigilance and surveillance has to be necessitated to ensure the time bound elimination of associated hazardous metal(loid) biomagnification throughout the surrounding eco-system from informal microscale e-waste recycling/operational activities. The results of this study may

also help global policymakers to make skilful management (both environmental and economic) of ongoing e-waste microscale sites, notably in SE Asia.

Microscale e-waste management – challenges and implications

The informal sector of e-waste handling/operation must be viewed in large and microscale perspectives in India (Dasgupta 2016; Saha et al. 2021) as well as SE Asia (Purchase et al. 2020). In large sector, the field-scale e-waste handling activities are often mechanized, partially skilful and regulated, whereas microscale informal sectors have been deeply involved with non-mechanized, primitive, and unscientific practices (Dasgupta et al. 2017). As a result, the microscale sectors are often producing relatively wider and uncontrollable eco-hazard concerns in comparison to largescale sectors. There are several microscale e-waste handling hotspots (Dasgupta, 2016) identified in rural areas which are historically driven by predominantly agriculture-based socio-economic livelihoods. These are gradually becoming a major threat jeopardizing the safety and sustainability of the entire ecosystem. These unprecedented microscale e-waste operational practices are often unexplored by both researchers and enforcing agencies (Arya and Kumar 2020).

In India, the fundamental and comprehensive e-waste management was first introduced in the form of "E-waste Management and Handling Rules, 2011" in schedule 1 under rule 2 (MoEF 2011). The legislation proposed extended producer responsibility (EPR) along with awareness to overcome the challenges of e-waste management, notably in the microscale informal sectors. The details of the rule including salient features and major drawback are depicted in Table 2. The e-waste management rule was amended in 2016 and reintroduced in 2017 (Table 2). The amendments proposed dedicated division of the responsibilities and involvements among several parties such as consumers, scrap dealers, dismantlers, recyclers, collection centers, producer/ manufacturer, re-retailers, and refurbishers that was limited in 2011. Additionally, the Producer Responsibility Organization (PRO, authorized organization to ensure safe channelization and systematic operation) was also brought under the purview of the 2017 legislations. The legislation also expanded to examine the components of EEE items in addition to the equipment (Table 2) (MoEF 2016).

However, it has been observed that though there has been a notable augmentation in the formal e-waste processing capacity after the implementation of the rules, in reality, a negligible percentage of the total waste generated (5–15%) is getting processed through formal sector. The concept of EPR in India should surpass simple take-back mandates and must concentrate into other policy instruments, e.g., deposit refund system, which has been

introduced as an additional economic instrument within the ambit of 2017 legislation (Table 2). Import of new EEE items could only be permitted under the provision of sub-rules (1 and 4) and rule (16) under restricted condition to restrain from adding more e-waste generation (MoEF 2016). The legislation (2017) was further amended in 2018 to address the lacunas in the existing rules, and also, for making efforts to accelerate the eco-friendly management of e-waste with the help of EPR and PRO to ensure proper collection and their efficient treatment in the formal sector (Table 2). However, the existing policies do not undertake to restrain microscale activities notably in the backyard of rural areas for the entire e-waste value chain in the country (Arya and Kumar 2020).

The present study indicates that both water and soil environment have been contaminated with elevated levels of hazardous metal(loid)s viz. Pb, Cd, Cu, Zn, and in some cases As above the respective safe limits, due to the practice of microscale e-waste recycling/recovery activities. In this context, the manufactures/producers, consumers, scrap dealers, dismantlers, and recyclers have to be accountable for ecosystem damage by increasing hazardous metal(loid)s load in the microscale sites. A coordinated effort is essential to bring all stakeholders notably manufactures, consumers, PCBs (both central and state), and local authorities under the single umbrella. This is important to maintain proper e-waste collection and channelization into the formal sector for treatment. This should protect the eco-system especially from microscale informal sector. The major challenge is to achieve time bound phasing out (transformation of informal sector to formal treatment option operation) of microscale e-waste practices. Phase I will be reviewed for skill development to ensure user-friendly collection and channelization, adopting eco-friendly treatment options (case-to-case basis), bank loan (low interest up to 2% annually), and awareness to prevent eco-system and human health degradation. Phase II will be the integration of phase I with technology-based monitoring and surveillance program (e.g., drone application) in microscale sites. This will be followed by infrastructural improvement (including manpower) with the help of PPP (public–private partnership) and CRTO (channelization–recycle-treatment-operation) for sustainable growth. Phase III will be validation of best practices, risk analysis, and data management for policy regulation. The action plan, if successfully augmented, will reduce the number of existing microscale sites thereby protecting surrounding water and soil environment.

Table 2 Salient features of different E-waste related legislations

E-waste related legislations	Salient features	Major drawbacks
"E-waste (Management and Handling) Rules, 2011"	• Concept of extended producer responsibility (EPR) introduced to overcome the challenges of e-waste management, notably in the micro-scale informal sectors • The roles and responsibilities of the collection centers, bulk consumers, dismantlers and recyclers well defined • Procedures for seeking authorization and registration for handling of e-wastes and storage of e-waste delineated	• Applicable only for electrical and electronic equipment (EEE) as listed in Schedule I • No set collection targets, resulting in major obstacle for ground level implementation
"E-waste (Management) Rules, 2016"	• Manufacturer, dealer, refurbisher, and Producer Responsibility Organization (PRO) introduced as additional stakeholders in the rules, with their responsibilities clearly defined • The applicability of the rules extended to components, consumables, spares and parts of EEE in addition to equipment as listed in Schedule I • Compact fluorescent lamp (CFL) and other mercury-containing lamp have been brought under the purview of rules • Collection mechanism–based approach adopted to include collection center, collection point, take back system etc. for collection of e-waste by Producers under EPR • Deposit refund scheme (DRS) introduced as an additional economic instrument, producer charges an additional amount as a deposit at the time of sale of the EEE and returns it to the consumer along with interest at the end—of—life of purchased EEE • The roles of different state government departments defined in the Rules • Urban Local Bodies have been assigned the duty to collect and channelized the orphan products to authorized dismantler or recycler	• Despite having a notable augmentation in the formal e-waste processing capacity after the implementation of the Rules, only a meager percentage of the total waste generated (5–15%) is likely to get processed through formal sector • The EPR framework forced the producers to address only a few relatively less significant aspects of the rules • The collection and recycling system were not made accessible for the consumers to dispose their e-waste in formal collection and recycling units
"Amendments in "E-waste (Management) Rules, 2016", made in 2018"	• The e-waste collection targets under EPR revised and made applicable from 1 October, 2017. The phase-wise collection targets for e-waste in weight shall be 10% of the quantity of waste generation as indicated in the EPR Plan during 2017–2018, with a 10% increase every year until 2023. From 2023 onwards, the target has been made 70% of the quantity of waste generation as indicated in the EPR Plan • The quantity of e-waste collected by producers from the 1 October 2016 to 30 September 2017 was accounted for in the revised EPR targets until March 2018 • Separate e-waste collection targets have been drafted for new producers, i.e., those producers whose number of years of sales operation is less than the average lives of their products. The average lives of the products will be as per the guidelines issued by CPCB from time to time • PROs were asked to apply to the CPCB for registration to undertake activities prescribed in the rules • Under the reduction of hazardous substances (RoHS) provisions, cost for sampling and testing was proposed to be borne by the government for conducting the RoHS test. If the product does not comply with RoHS provisions, then the cost of the test will be borne by the producers	• Field application of the EPR amendment rule limited to meet the collection target • Notification required to account the revised target • CPCB guidelines inadequate to use average lives of the products • Regular testing and non

Both federal and state/local government will come forward for the implementation of action plan (phasing out of the informal sector) for the purpose of improving the microscale ground reality. From management perspective, a scheme is proposed following a relationship between different stakeholders and tools, for the improvement of e-waste management in south-east Asian countries (Supplementary Fig. S11). Several influencing factors such as numerous inputs and their connectivity, role of local authorities (municipality and panchayat), surveillance support by enforcing agencies (PCB), role of producers and consumers, importance of formal sector and task of interface organizations (public awareness, registration, tracking of e-waste, legal framework), regular monitoring, and surveillance are focused and summarized. This will provide a new roadmap and maximize the benefit in terms of environment and human health protection.

Presently, developed countries like Switzerland has introduced advance recycle fee (ARF) system and such fees can be revised based on the categorization of the electrical and electronic goods, expert views, and regular consultation with the industry (Hischier et al. 2005; Khetriwal et al. 2009). Additionally, the present study proposes that industries should be intensely involved with technical expert groups to build up an effective ARF system, along with its maintenance and periodic revision. An apex body will help maintaining the interconnectivity between consumers and producers and appraising government, so that existing rules can be modified or regulated in terms of ARF, eco-labelled products, and collection center as and when required. Although the amended laws in India have come into place, the microscale informal sector has overall control on e-waste handling and disposal, which is to be continued at the cost of huge health and environmental cost polluting groundwater and soil. In this context, the proposed improved e-waste management practice will be a new roadmap for several south-east Asian countries to protect the eco-system and human health, including microscale informal sites in India such as the one monitored in this study.

Conclusion

The highlight of the study was the observations based on the microscale informal e-waste recycling sites in rural India. Water and soil samples have elevated levels of monitored hazardous metal(loid)s (Pb, Cd, Cu, Zn, As, Hg, Ni, and Cr). However, the concentrations are consistently low to very low in the water environment, suggesting restricted dissolution of harmful metal(loid)s from soil. However, Cd, Pb, Cu, and Cr are detected above the national drinking water safe limit. Consequently, the public health risk is associated with pond waters

that are used for e-waste handling/dismantling. Because these ponds are usually flooded during the monsoon season and may mix with further larger water resources. On the other hand, the monitored soil samples (both top and subsoil) are consistently dominated with enriched levels of hazardous metals (Pb, Cd, Cu, and Zn) when compared to the control site. This could impose a future risk in terms of accumulation and biomagnification of these metal(loid)s through various routes, e.g., water or food crops. Moreover, soil pollution may remain a matter of concern, as the chemical behavior (availability of relatively mobile soluble form and oxidation state) may play a key role to mobilize the metals in the subsurface environment.

The seasonal variations of soil metal(loid) content were evident as well. The Pre M (November–May) levels were higher in case of most of the metal(loid) concentrations than the Post M season (June–Oct) possibly due to the monsoon driven dilution effects. Except for Pb and Cd, where their respective Post M concentrations increased. This is possibly because they produce less labile and mobilizable species under the enriched reducing conditions (high Eh, low pH) as well as organic matter availability and perhaps choose to remain adsorbed to the host soil. Further investigation is needed to test these findings. The variation, distribution, and behavior of monitored hazardous metal(loid)s are also primarily dependent on the type of e-waste being processed, and the manual handling/sorting/separating/dismantling/treatment method seemed to have a great influence on the levels of hazardous metal(loid)s being released in the ambient environment.

The current study largely focuses on the microscale e-waste handling and operational activity in rural areas which is often underreported by the researchers as well as regulatory agencies. The results also depict the harmful environmental and ecological risks which, if studied further, may unravel larger threats. The key finding is the focused surveillance and vigilance of the rural microscale sectors and, either their monitored regularization or stopping them from causing any environmental, ecological, and economical safety and sustainability of rural livelihoods. In India, the e-waste legislation (2011) and subsequent amendments (2016, 2017, 2018) are already implemented. However, field investigation suggests that the microscale informal sector environmental perspective (almost) remains unchanged. In this context, a skillful e-waste management model has been designed to accelerate the implementation process to ensure rapid growth of formal sectors and quick abolition of informal sectors, notably open burning. The model accommodates several judicious steps (connectivity among key players, strengthening local authorities, strong surveillance, public

awareness, and producer/consumer relationship) to face the challenges, a gray area of e-waste management in entire south-east Asia.

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Author contribution

Debashis Chatterjee and Santanu Majumder contributed to the study conception and design. Material preparation, experimental analysis, data collection, and material preparation were performed by Dipsikha Dasgupta, Santanu Majumder, and Debashis Chatterjee. The first draft of the manuscript was written by Dipsikha Dasgupta, followed by rigorous detailed revisions by Debashis Chatterjee and Santanu Majumder. Jishnu Adhikari, Pinaki Ghosh, Diane Purchase, Hemda Garelick, and Anupam Debsarkar — they all have been intellectually involved during the primary inception of the study and commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

All data generated or analyzed during this study are included in this article.

Declarations

Ethics approval

This research work does not involve any human participants and/or animals.

Consent for publication

All authors approved the final manuscript for submission and publication.

Competing interests

The authors declare no competing interests

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