

Assessment of Relative Hazard Potential of Popular e-Waste Categories during Landfilling

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Abstract: Electronic waste (e-waste) has become the fastest growing component in solid waste stream. Lack of data regarding characterisation of these e-waste categories and their hazard potential poses further challenge for setting up or planning of proper recycling and disposal facilities for them. The present study aims to assess relative hazard potential of popular e-waste categories such as laptop computers, mobile phones, radio sets, electronic calculators and electronic toys, which form a substantial amount of total e-waste. Samples of these e-waste categories were collected, dismantled and leached to specifically identify various plastic and metal fractions from each category. Leachates (by simulating conditions of landfilling) were prepared under different pH conditions and analysed for contents of hazardous metals. The current study could provide a basis for modelling different intervention options and predicting their effects. The findings could be utilised to support efforts to arouse and enhance public awareness regarding environmental protection by publicity and education to guide consumer preferences to support products that are manufactured with and ultimately generate little hazardous or solid waste.

Key words: E-waste, characterisation, relative hazard potential, landfilling, heavy metal contamination.

Introduction

Electronic waste or e-waste is the term used to describe old, end-of-life electronic appliances such as computers, laptops, TVs, DVD players, mobile phones, MP3 players, etc., which have been disposed by their original users (eWaste guide, available from <http://www.ewaste.in>). The changing lifestyle of people, coupled with urbanisation, has led to increasing rates of consumption of electronic products. Driven primarily by faster technological innovation and consequently a high obsolete rate, this catalogue of new wastes poses a direct challenge for its proper disposal or recycling in the present set up, is expensive and requires technical know-how. The dumping of e-waste, particularly computer waste, into India from developed countries (Wankhede, 2005) ('green passport' according to Harder, 2005),

because the latter find it convenient and economical to export waste, has further complicated the problems with waste management. The issue has assumed serious global dimensions as e-waste creates serious worker, community and environmental problems, not only in production but also at the waste end.

The composition of WEEE/e-waste is very diverse and differs in products across different categories. It contains more than 1000 different substances, which fall under 'hazardous' and 'non-hazardous' categories. Broadly, it consists of ferrous and non-ferrous metals, plastics, glass, wood and plywood, printed circuit boards, concrete and ceramics, rubber and other items. Iron and steel constitutes about 50% of the WEEE followed by plastics (21%), non-ferrous metals (13%) and other constituents. Non-ferrous metals consist of copper, aluminium etc. and precious metals, e.g.

silver, gold, platinum, palladium, etc. The presence of elements like lead, mercury, arsenic, cadmium, selenium and hexavalent chromium and flame retardants beyond threshold quantities in WEEE/e-waste classifies them as hazardous waste (CPCB website, available from <http://www.cpcb.nic.in/Electronic%20Waste/Chapter1.html> and <http://www.cpcb.nic.in/Electronic%20Waste/Chapter2.html>).

Several studies have attempted to characterize e-waste but most of them are limited to desktop computers (Jang et al., 2005; Li et al., 2006). Though computer waste is one of the significant components, laptop computers, mobile phones, hand video games, calculators, radio sets, etc. constitute other significant category of electronic waste.

The use of these items is going to increase in the coming years due to advancement in technology and increase in demand. Currently, the discard rate for a mobile phone or a video game is more as compared to a desktop computer. People change their cell phones in six months while they change their desktop computers after 4-5 years. Similarly, a hand video game is hardly used for about 3-4 months and ends up as a waste item later. As these categories are becoming significant, there is a need for their characterisation.

Due to the lack of governmental legislations on e-waste standards for disposal, proper mechanism for handling these toxic hi-tech products mostly end up in landfills or partly recycled in unhygienic conditions and partly thrown into waste streams. While having some of the world's most advanced high-tech software and hardware developing facilities, India's recycling sector can be called medieval (Swerts, 2006). Impacts resulting from the recycling and disposal of e-waste have been reported in many countries, particularly in Asia (Brigden et al., 2005; Wong et al., 2007; Leung et al., 2007).

Some prominent areas where informal recycling is being done in Delhi (capital city of India) are old Seelampur, Shastri Park and Mandoli. The recycling is limited to copper compounds, certain precious metals like gold and silver, and lead from circuit boards and batteries (Basu, 2008). Apart from these, other non-recyclable materials like plastic residues from IC chips and condensers are generally dumped in open fields and drains around dismantling and recycling areas.

There are different options available for managing e-waste in an environmentally sound framework. These options can be broadly categorized under Reuse, Recycle, Incineration and Landfilling. It is to be noted that incineration of e-waste is being discouraged worldwide because of the generation of toxic substances

such as furans and dioxins in the environment. Each of these management options has different cost and risk implications and there is a clear reason to be concerned about the management scheme for computer waste, which is both cost effective and safe. However, each component of computer waste has different set of toxic substances/elements in varying amounts. This complicates assessment of risk from associated waste management activities.

Proper management of WEEE is a concern that has been recognized by both government agencies and the general public. In order to accelerate the rate at which proper processing and management methods are employed, timely regulatory and legislative policies and procedures are needed. It is important that these requirements be addressed in a proactive manner.

For this a pre-requisite is to clearly understand the characterisation of these wastes, which is challenging because they tend to be quite heterogeneous and complex in terms of the type, size and shape of components and materials and ascertain the hazard posed. Therefore, continued in-depth and multidisciplinary approach is needed.

Literature Review

The current section summarises selected studies on e-waste characterisation and relative hazard assessment to provide an adequate background to the current study.

E-waste Characterisation

To-date, no systematic analysis of the substance flows (i.e., of chemical elements and compounds) associated with the disposal of WEEE exists. In a study, Vehlow and Mark (1997) and Mark and Lehner (2000) had determined concentrations of selected elements in electrical and electronic plastic waste fractions. Cui and Forssberg (2007) carried out characterisation of TV scrap by using a variety of methods, such as chemical analysis, particle size and shape analysis, liberation degree analysis, thermogravimetric analysis, sink-float test, and IR spectrometry. The study on comparison of TV scrap, personal computer scrap, and printed circuit board scrap concluded that the content of non-ferrous metals and precious metals in TV scrap was much lower than that in personal computer scrap or printed circuit board scrap.

Several studies have broadly characterised the various components of WEEE. It has been estimated that about 66% of WEEE by weight consists of metals

such as iron, copper, aluminium and gold and non-metals, while other pollutants make up about 34% of the waste. Ferrous metal is the most common material found in electric and electronic components (Morf et al., 2006). Data from Ireland show that iron and steel comprise almost half of the total national WEEE waste, which is estimated to be between 25,000 and 30,000 tonnes per year (WEEE, 2001) while non-ferrous metals such as aluminium, copper and some precious metals make up about 13% of their WEEE waste stream (ETC/RWM, 2003). Glass accounts for an estimated 5.4% of the total weight of waste from electric and electronic equipment every year (Theisen, 2002). Plastics were estimated to be the second largest component by weight, accounting for approximately 21% of WEEE in Ireland (as of 2001) (Wilkinson et al., 2001). There is an added danger that some of this plastic is flame retardant and can be damaging to the environment if not disposed off properly. Several studies have reported selective disassembly (dismantling in the practice of recycling WEEE) as an indispensable process to remove hazardous or high value components (Cui and Forssberg, 2003; Stuart and Christina, 2003; Basdere and Seliger, 2003; Torres et al., 2004). Characterising WEEE consumer electronic equipment has been stated as an imperative requirement in order to develop a cost effective and environmentally friendly recycling system (Zhang and Forssberg, 1997). The same holds true for other management options such as landfilling.

Relative Hazard Assessment

OTA (1981) concluded that a well-designed degree-of-hazard classification system might provide a strategy for cost-effective management of non-nuclear industrial hazardous waste. They stated that it would be important to choose several degrees of hazardousness and not to exclude types of waste, such as those generated in relatively small quantities and some chemicals with known chronic (long-term) toxicity, without making assessments of the levels of hazard they pose to the public. The study further stated that a qualitative degree-of-hazard approach without specific categories required less effort to develop criteria and data, and its apparent simplicity might be attractive from a programmatic perspective. In the long term, however, such an approach could prove to be inefficient, since scientific information appropriate for classification might be needed in the future.

Jennings and Suresh (1986) presented an algorithm that used an analytical solution of the fuzzy decision alternative ratio evaluation analysis to generate risk

penalty functions for hazardous waste management planning. The procedure was based on a series of ratio evaluations that could be made using any existing hazardous waste ranking or rating procedure, or any combination of existing methods and the required input could be purely subjective, facilitating assessment of relative risk.

Eriksson et al. (1989) demonstrated a strategy for toxic hazard ranking of environmentally occurring chemicals on two data sets, chlorinated aliphatics (AX), and aliphatic alcohols (AAC). The strategy was based on the assumption that a small set of chemicals could be identified that represented all other compounds within a structurally homogeneous class. The subset was selected according to a statistical experimental design and was especially suitable as a training set for quantitative structure-activity relationships (QSARs). The QSARs were subsequently used to predict biological activity data for untested compounds in the class of interest.

Haness and Warwick (1991) discussed the hazard ranking system used by the EPA to evaluate the relative risk of hazardous waste facilities. The research concluded that small increases in data could significantly increase a facility's score if applied to influential system factors. However, the identification of influential factors was difficult. The study stated that factor importance was site specific, dependent upon the values of other system criteria, and that its evaluation was impeded by the additive/multiplicative structure of the ranking system.

Hill and Babad (1991) carried out a study to resolve the known safety and technical issues associated with the eight organic waste tanks. Resolution of these issues was done with an objective to lead to safe disposition of the tank contents either by mitigation, remediation, or interim stabilisation until final disposal. Activities associated with issue resolution included short and long term safety assessments, management and control of tank storage operations, collection and analysis of tank historical information as well as characterisation and testing of tank waste samples.

Tyler et al. (1994) introduced a technique to determine the toxicity hazard potential of a single chemical. As a result the developed toxicity index was inadequate when one considered the evaluation of toxicity of a hazardous waste such as waste computers which were a conglomeration of numerous toxic chemicals.

Khan and Abbasi (1998) presented a system of methodologies for Hazard Identification and Ranking (HIRA). The system consisted of two indices: one for fire and explosion hazards and another for the

hazard due to likely release of toxic chemicals. The magnitudes of these indices were intended to indicate the severity of the likely accident; in terms of the size of the impacted area. HIRA was applied to a typical chemical process industry—a sulfolane plant—and its performance was compared to that of the Dow's and the Mond's indices.

Gupta and Suresh (1999) proposed an index that measured hazards related to flammability, reactivity, toxicity and corrosivity as well as the pH value for a hazardous waste and demonstrated it for two example problems. Its purpose was to facilitate decision-making during handling, transporting, treating and disposal of or recycling hazardous wastes. However, in the development of this index, no attempt was made to integrate the indices related to flammability, corrosivity, toxicity and reactivity into a single-value output representing the overall hazard ranking of the composite waste.

Nema and Gupta (1999) proposed a function for addressing risk to the environment in relative terms. Risk was considered as the function of waste quantity, hazard potential (HP) of the waste, probability of accident, and receptor population impacted in case of accident.

Stenner et al. (1999) proposed a methodology to provide a means of calculating the relative hazard ratios to be used in developing useful graphic illustrations. The relative hazard equation, as presented in this methodology, was primarily a collection of key factors relevant to understanding the hazards and risks associated with projected risk management activities.

Vrijheid et al. (2002) developed and evaluated an expert panel scoring method of the hazard potential for Eurohazcon landfill sites, and investigated whether sites classified as posing a greater potential hazard were those with a greater risk of congenital anomaly among nearby residents relative to more distant residents. An expert panel of four landfill specialists scored each site in three categories—overall, water and air hazard—based on readily available, documented data on site characteristics. Tertiles of the average ranking scores defined low, medium and high hazard sites.

Donoghue (2001) described the construction of two qualitative and semi-quantitative hazard risk assessment matrices. The first matrix used qualitative measure of both probability and consequence. The second matrix used attributable risk as a quantitative measure of probability, while using qualitative measures of consequence. Both matrices classified consequence

using the terms of death, permanent major disability, permanent minor disability and temporary disability.

Pittinger et al. (2003) identified seven categories of risk assessment tools based on information content, function and type of output produced. The categories identified were Physical-chemical data and Structure-Activity Relationships (SAR); Hazard data and Quantitative Structure-Activity Relationships (QSAR); Exposure data and models; Screening and scoring tools; Screening-level risk assessment with available data, predictions and conservative exposure estimates; Higher-tiered risk management with more empirical, measured data and refined exposure data; and, Validation and Monitoring.

Christensen et al. (2003) concluded that though the terminology in risk assessment procedures differed significantly, the initial step in all risk assessment procedures was the problem/hazard identification.

Numerous ranking procedures and screening tools for hazard identification of chemical substances that have been proposed so far, focus on priority setting for chemical regulation purposes (Swanson and Socha, 1997; Hansen et al., 1999; Snyder et al., 2000).

Rao et al. (2004) presented a method using NFPA hazard rankings for flammability, corrosivity, reactivity and toxicity to calculate risk indices of chemicals they posed during the transportation of hazardous wastes. Among the factors incorporated in this method were the quantity of material being transported, the distance between the point of release and human populations in the proximity, rate of dispersion and the probability of an accident occurring. As the factors considered in their study were related to transportation, the derived index had limited applicability in hazard ranking of chemicals in other processes, such as disposal, production and recycling.

Pittinger et al. (2004) expanded on their earlier study (Pittinger et al., 2003) of a conceptual model of hazard and risk ranking tools, wherein some 100 chemicals were ranked based on scoring approaches (developed by a variety of sources, including state, regional, federal and international regulatory agencies) used globally. A case-study approach for five High production volume (HPV) chemicals (acrylonitrile, benzene, ethylene glycol, vinyl acetate and zinc) was used to identify commonalities and differences among results obtained when applying diverse hazard ranking approaches. The study concluded that relative hazard rankings for given chemicals differed markedly among the approaches evaluated. This was attributed to distinct differences in the toxicological and transport-and-fate criteria applied

under each approach. Based on this analysis, it was evident that no single method addressed all decision-making needs. Comparative evaluation and judicious weighing of chemical hazard results provided the most sound and accurate information to support a wide range of applications.

Atmaca and Hahn (2004) described the methodology and results of the environmental investigations which were carried out to assess the hazard potential and the remediation options of abandoned mine sites, especially tailings dumps, in Chile and Peru. The methods applied comprised a geochemical programme, mineralogical and metallurgical investigations and geotechnical studies. The geochemical programme included the drilling of tailings dumps and the collection of tailings samples, stream sediments, soil and water samples, in situ measurements of physicochemical parameters of water, and the analysis of the samples. The mineralogical and metallurgical investigations comprised x-ray diffraction studies and electron microprobe analysis of tailings material to determine the (ore) minerals, their mode of occurrence, grain sizes, and the distribution of the metals, especially gold and silver. The geotechnical investigations of the project dealt with risks to humans or the environment, i.e. open shafts, adits and ramps, ruined mine buildings, stability of tailings dumps and earth dams, collapsed ground, toxic chemicals, scrap metal heaps, and tailings dust.

Similar to the parameter HP proposed by Nema and Gupta (1999), Talinli et al. (2005) proposed an overall rating value for hazardous waste by using variables such as ecological effect (ignitability, reactivity, corrosivity, toxicity) and combined potential risk (carcinogenic effect, toxic characteristics, infectious characteristics, persistency).

Baun et al. (2006) presented a methodology (RICH: Ranking and Identification of Chemical Hazards) for ranking and identification of xenobiotic organic compounds of environmental concern in stormwater discharged to surface water. The RICH method was illustrated as a filter to sort out problematic and hazardous compounds based on inherent physicochemical and biological properties. The outcome gave separate lists for both water phase and solid phase associated compounds.

Jarvis (2006) developed a Radiological Hazard Potential (RHP) with an aim to facilitate systematic and progressive reduction in hazard. The RHP reflected an emphasis on hazard potential and its reduction (colloquially harm cannot be realised) rather than the more traditional safety analysis which focused on risk

(colloquially harm will not be realized). The resulting RHP was designed to be a relative, rather than an absolute measure, allowing comparison between different radioactive materials and between materials stored in different forms at different locations. It was argued that different radionuclides presented widely differing hazards, and physical measures such as volume or activity did not take this into account. Hence, the inventory term chosen was the ingestion toxic potential (ITP) of the waste which took into account factors such as the specific nature of individual radionuclides in terms of their half life and persistence in the body to calculate a theoretical dose. The ITP was a quantity derived from Annual Limits on Intake, an internationally accepted concept and was proposed as the volume of water required to dilute the material to a concentration that would be safe to drink if a population used the mixture as its sole source of drinking water. For certain radionuclides that presented a greater hazard to humans through inhalation rather than ingestion, the inventory term was modified as a measure of prudence.

Misra and Pandey (2005) concluded that the degree of hazard posed by wastes might be dependent on several factors, such as physical form, composition, reactivity (fire and explosion) and quantities; biological and ecological effects (i.e. bioavailability, toxicity, ecotoxicity); mobility (i.e. transport in various environmental media, leaching potential); persistence (including fate in environment, detoxification potential, secondary transformation); indirect health effects that might result from pathogens, vectors, etc.; local conditions (e.g. temperature, soil types, ground water table conditions, humidity, light, etc.).

Musee et al. (2006) presented a fuzzy index as a measure of hazardousness of a given composite waste. The index was derived from the crisp inputs of its components' flammability, corrosivity, toxicity and reactivity attributes based on National Fire Protection Association hazard ratings.

Musee et al. (2008a) stated that for hazardous waste classification the criteria used were mostly based on physical properties, such as quantity (weight), form (solids, liquid, aqueous or gaseous), the type of processes generating them, or a set of predefined lists. Such classification criteria were inherently inadequate to account for the influence of toxic and hazard characteristics of the constituent chemicals in the wastes, as well as their exposure potency in multimedia environments, terrestrial mammals and other biota. Second, none of these algorithms in the literature had explicitly presented waste classification

by examining the contribution of individual constituent components of the composite wastes. They proposed an algorithm for waste classification that took into account physicochemical and toxicity effects of the constituent chemicals to humans and ecosystems, in addition, to the exposure potency and waste quantity. In the first part, available data on the physicochemical and toxicity properties of individual chemicals in humans and ecosystems, their exposure potency in environmental systems and the effect of waste quantity were described, because they fundamentally contributed to the final waste ranking. Knowledge acquisition in this study was accomplished through the extensive review of published and specialised literature to establish facts necessary for the development of fuzzy rule-bases. Owing to the uncertainty and imprecision of various forms of data (both quantitative and qualitative) essential for waste classification, and the complexity resulting from knowledge incompleteness, the use of fuzzy set theory for the aggregation and computation of waste classification ranking index was proposed. A computer-aided intelligent decision tool was described in part II of this paper (Musee et al., 2008b) and the functionality of the fuzzy waste classification algorithm was illustrated through nine worked examples.

WEEE has several significant issues of risk associated with it owing to its hazardous nature. The risk can be risk to the environment as a whole, which can include risk posed to human beings and the environment during its management in case of an accident. Quantification of accidental risk to the environment in absolute terms is a complex and difficult exercise due to lack of data regarding the probability of accident and/or its consequences (Kirchsteiger, 1999). Several researchers have attempted to quantify this risk in relative terms. However, for such quantification, assessment of relative hazard from the different waste categories is a pre-requisite. Musee et al. (2006) has stated classification of hazardous wastes in terms of their toxicity, flammability, corrosivity and reactivity as one of the greatest challenges in dealing with them. The challenge is aggravated by the high risks involved, lack of sufficient time and huge financial costs required to study a large range of different wastes. Moreover, there is a need to have a systematic methodology to integrate all hazardous attributes into a single measure of the hazardousness of a particular waste category.

Also, in certain cases, classical methods have led to inconsistent results, since unavailable data are usually estimated according to averaged values or using values

of similar elements which may not be a true reflection of the substances in the composite hazardous wastes. Furthermore, these methodologies sometimes introduce excessive accuracy in their calculations, which may be unwarranted by the uncertainty of the available data. Although methodology for assessment of hazard potential has been proposed in several studies, most of these require tedious investigations and analysis and provide only indicative results. Therefore, there is still a need for a systematic and easy-to-use tool that can be used to rank the hazardousness of a particular waste by taking into account all the waste characteristics. Also, hazard potential not only varies from one waste category to another, it also varies from one management option to the other. Furthermore, sound assessment of hazard potential requires details pertaining to WEEE characterisation specific to the management option for which hazard potential is being assessed.

Objectives and Scope

The present study aims to assess relative hazard potential of various e-waste categories during landfilling based on heavy metal concentrations leached under different pH conditions. The scope of the work is limited to the collected e-waste items like old video games, cell phones, calculators, walkman, and radio sets, etc.

Materials and Methods

Following methodology was adopted for characterisation of e-waste streams and evaluation of relative hazard potential.

Sample Collection

The samples (waste electronic items) were collected from waste/scrap dealers in Nehru Place area of New Delhi and from residential establishments. Items collected had been manufactured between the period 1995 and 2006. Batteries were not included in the analysis.

Dismantling and Segregation

The collected items were dismantled, broken and segregated into several material components, comprising mainly of (i) plastic, (ii) metal, (iii) glass, (iv) rubber, (v) wires, (vi) printed circuit boards with integrated circuits, (vii) capacitors, (viii) ceramic, and (ix) other materials like composites. Dismantling was done manually with hammer, screw driver and chisel, etc. Proper precautions were followed during dismantling, i.e., wearing gloves

and protective glasses. The material fractions were segregated and weighed. These were further broken into smaller size (1-2 cm) by hammer. This size reduction was done to make the material convenient for storage and further processes. Fractions were stored in plastic bags and labelled.

Estimation of Different Metal Fractions

The concentration of heavy metals can be estimated using TCLP test (EPA, 1992) (refer Appendix I). Toxicity of electronic wastes has been estimated in terms of heavy metal concentrations by leaching procedures like TCLP in several laboratory based studies (Dimitrakakis, 2009; Sastre et al., 2002; Gullet et al., 2007). However, in the present study modified TCLP procedure has been deployed as it has been argued that standard TCLP procedure simulates the worst case scenario (of waste being co-disposed with municipal solid waste (MSW) in the landfills) and takes into account leaching of metals only in the acidic environment resulting in overestimation of their leached concentrations (Halim et al., 2005).

Concentrations of various heavy metals were calculated for the three pH conditions (pH = 2 representing acidic environment; pH = 7 representing neutral environment and pH = 12 representing acidic environment). Leachates were prepared under different pH conditions and analysed for contents of hazardous metals. Total of eight heavy metals (cadmium, chromium, copper, lead, iron, manganese, nickel and zinc) in the waste samples were analyzed. The process deployed is listed below:

1. One representative sample (5 g) each of plastic and (PCB+ IC) was taken from every item. Samples were reduced manually to a size of 0.95 cm as required by standard TCLP for maximum leaching.
2. Each 5 g sample was mixed with 100 ml ultra pure water with pH of about 7.
3. The process was repeated for ultra pure water of pH 2 (nitric acid) and pH 12 (sodium hydroxide).
4. Samples were leached for 24 hours at 35 degree Celsius and a rotation of about 100-110 rpm in orbital shaker.
5. Leachate was filtered and was digested using 20 ml concentrated HCl.

Digested samples were analyzed for metal concentration in an atomic absorption spectro photometer (AASP model number AAS4141, ECIL—Electronic Corporation of India Limited).

Estimation of Relative Hazard Potential

In order to compare the relative risk posed by the various electronic waste items during disposal, concentration of each metal fraction in the leachate was multiplied by its importance factor (refer Table 1) (Ahluwalia and Nema, 2007). Non-cancer Oral Risk (NCOR) values [as available in toxicity database of International Toxicity Estimates for Risk Database (ITER), available from: www.iter.org] were considered a basis for arriving at the Importance factor, which was a parameter defined to quantify characteristics. The minimum of the reported NCOR Values (mg/kg-day) from each of the database was chosen. The chemical/parameter with a maximum value of risk dose and hence relatively lowest risk potential (titanium) was assigned the value of importance factor as 1. Other chemicals were then assigned importance factors based on the ratio of risk dose of titanium to risk dose identified for them. Inverse linear relationship between the NCOR value and risk per unit quantity was assumed i.e., a chemical/component with lesser value of NCOR would result in a higher risk by the same ratio.

Table 1: Importance factor of different metal fractions in e-waste

<i>Component</i>	<i>Importance factor</i>
Plastics	15.0
Lead	833.0
Copper	21.4
Nickel	150.0
Zinc	10.0
Manganese	21.4
Chromium	1000.0
Cadmium	15000.0
Iron	0.0

Results and Discussion

Concentrations of various heavy metals for the three pH conditions are presented in Tables 2a, 2b, 3a, 3b, 4a and 4b.

The composition of selected WEEE can change significantly both due to legislative provisions and in the wake of technical, economic and social developments. Chemical analysis of the substances contained in WEEE therefore represents a useful procedure, not only in monitoring performance at the material flow level, but also in determining changes in composition and in assessing the efficacy of legislative, organisational and technical measures/management options on the WEEE.

Table 2a: Concentration of metals for samples leached in acidic medium (pH = 2)

Sample number	Sample name	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
1.	Calculator (Brand "C _A ") plastic	BDL ^a	0.080	0.208	4.140	0.668	1.319	1.652	0.668
2.	Mobile phone (Brand "MP _C ") plastic	0.007	BDL ^a	3.093	2.318	0.050	1.947	0.990	0.563
3.	Video game (Brand "V _A ") plastic	BDL ^a	BDL ^a	1.428	1.134	0.038	0.659	0.211	0.395
4.	Video game (Brand "V _B ") plastic	BDL ^a	BDL ^a	BDL ^a	BDL ^a	BDL ^a	0.219	0.013	0.050
5.	Radioset (Brand "R _A ") plastic	BDL ^a	BDL ^a	1.307	0.448	0.036	1.727	0.257	0.595
6.	Laptop (Brand "L _A ") plastic	BDL ^a	BDL ^a	0.347	0.438	0.023	0.408	0.373	0.359
7.	Laptop (Brand "L _B ") plastic	BDL ^a	BDL ^a	2.416	1.943	0.056	1.910	0.798	0.575
8.	Walkman (Brand "W _A ") plastic	0.006	BDL ^a	1.878	1.480	0.046	0.683	0.552	0.478
9.	Mobile phone (Brand "MP _A ") PCB	0.002	0.001	2.365	3.790	0.164	4.170	4.148	0.652
10.	Mobile phone (Brand "MP _B ") PCB	0.001	BDL ^a	3.803	1.773	0.064	4.028	4.300	0.771
11.	Mobile phone brand "MP _C " PCB	0.013	BDL ^a	2.665	0.893	2.090	3.598	4.318	0.818
12.	Laptop (Brand "L _A ") PCB	BDL ^a	BDL ^a	1.243	0.254	0.004	2.865	4.083	0.463
13.	Laptop (Brand "L _B ") PCB	0.003	BDL ^a	3.638	0.458	0.083	4.045	4.165	0.652

^aBelow detection limit**Table 2b: Amount of metals for samples leached in acidic medium (pH = 2)**

Sample Number	Sample Name	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
1.	Calculator (Brand "C _A ") plastic	BDL ^a	1.605	4.165	82.800	13.350	26.370	33.045	13.365
2.	Mobile phone (Brand "MP _C ") plastic	0.135	BDL ^a	61.850	46.350	0.995	38.940	19.785	11.260
3.	Video game (Brand "V _A ") plastic	BDL ^a	BDL ^a	28.560	22.680	0.765	13.180	4.225	7.895
4.	Video game (Brand "V _B ") plastic	BDL ^a	BDL ^a	BDL ^a	BDL ^a	BDL ^a	4.380	0.265	0.995
5.	Radioset (Brand "R _A ") plastic	BDL ^a	BDL ^a	26.130	8.955	0.725	34.540	5.145	11.890
6.	Laptop (Brand "L _A ") plastic	BDL ^a	BDL ^a	6.945	8.750	0.460	8.150	7.450	7.180
7.	Laptop (Brand "L _B ") plastic	BDL ^a	BDL ^a	48.310	38.860	1.050	38.235	15.960	11.498
8.	Walkman (Brand "W _A ") plastic	0.120	BDL ^a	37.550	29.590	0.915	13.650	11.040	9.555
9.	Mobile phone (Brand "MP _A ") PCB	0.045	0.015	47.295	75.800	3.270	83.400	82.950	13.030
10.	Mobile phone (Brand "MP _B ") PCB	0.020	BDL ^a	76.050	35.460	1.280	80.550	86.000	15.425
11.	Mobile phone brand "MP _C " PCB	0.260	BDL ^a	53.300	17.860	41.795	71.950	86.350	16.355
12.	Laptop (Brand "L _A ") PCB	BDL ^a	BDL ^a	24.850	5.080	0.080	57.300	81.650	9.260
13.	Laptop (Brand "L _B ") PCB	0.060	BDL ^a	72.750	9.165	1.675	80.900	83.300	13.030

^aBelow detection limit**Table 3a: Concentration of metals for samples leached in neutral medium (pH = 7)**

Sample number	Sample name	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
1.	Calculator (Brand "C _A ") plastic	0.002	0.251	0.008	0.176	0.017	0.439	0.115	0.404
2.	Mobile phone (Brand "MP _C ") plastic	0.007	BDL ^a	0.877	0.925	0.403	0.651	0.267	0.427
3.	Video game (Brand "V _A ") plastic	0.001	0.410	0.087	0.228	0.031	0.423	0.115	0.350
4.	Video game (Brand "V _B ") plastic	0.001	BDL ^a	0.010	0.139	0.040	0.416	0.096	0.174
5.	Radioset (Brand "R _A ") plastic	0.002	0.388	0.094	0.155	0.029	0.471	0.138	0.249
6.	Laptop (Brand "L _A ") plastic	BDL ^a	0.080	0.032	0.207	0.019	0.439	0.161	0.230
7.	Laptop (Brand "L _B ") plastic	0.007	BDL ^a	0.131	0.139	0.025	0.486	0.175	0.255
8.	Walkman (Brand "W _A ") plastic	0.009	BDL ^a	0.098	0.228	0.040	0.471	0.354	0.360
9.	Mobile phone (Brand "MP _A ") PCB	0.007	BDL ^a	0.321	0.181	0.019	1.177	0.957	0.257
10.	Mobile phone (Brand "MP _B ") PCB	0.007	BDL ^a	0.012	0.170	0.017	0.628	0.294	0.592
11.	Mobile phone brand "MP _C " PCB	0.007	BDL ^a	0.145	0.248	0.029	1.680	0.676	0.452
12.	Laptop (Brand "L _A ") PCB	0.007	BDL ^a	0.014	0.066	0.017	0.863	0.308	0.142
13.	Laptop (Brand "L _B ") PCB	0.009	BDL ^a	0.034	0.108	0.017	1.539	0.211	0.253

^aBelow detection limit

Table 3b: Amount of metals for samples leached in neutral medium (pH=7)

Sample number	Sample name	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
1.	Calculator (Brand "C _A ") plastic	0.035	5.020	0.155	3.510	0.345	8.780	2.290	8.085
2.	Mobile phone (Brand "MP _C ") plastic	0.145	BDL ^a	17.530	18.490	8.050	13.020	5.330	8.545
3.	Video game (Brand "V _A ") plastic	0.020	8.205	1.740	4.560	0.615	8.465	2.290	6.990
4.	Video game (Brand "V _B ") plastic	0.020	BDL ^a	0.200	2.775	0.805	8.310	1.925	3.475
5.	Radioset (Brand "R _A ") plastic	0.045	7.750	1.875	3.090	0.575	9.410	2.750	4.970
6.	Laptop (Brand "L _A ") plastic	0.000	1.605	0.640	4.140	0.385	8.780	3.210	4.590
7.	Laptop (Brand "L _B ") plastic	0.145	BDL ^a	2.625	2.775	0.500	9.725	3.490	5.095
8.	Walkman (Brand "W _A ") plastic	0.185	BDL ^a	1.960	4.560	0.805	9.410	7.080	7.200
9.	Mobile phone (Brand "MP _A ") PCB	0.145	BDL ^a	6.415	3.615	0.385	23.545	19.140	5.140
10.	Mobile phone (Brand "MP _B ") PCB	0.145	BDL ^a	0.240	3.405	0.345	12.550	5.88	11.83
11.	Mobile phone brand "MP _C " PCB	0.135	BDL ^a	2.890	4.965	0.575	33.600	13.525	9.030
12.	Laptop (Brand "L _A ") PCB	0.145	BDL ^a	0.285	1.310	0.345	17.265	6.160	2.845
13.	Laptop (Brand "L _B ") PCB	0.170	BDL ^a	0.685	2.150	0.345	30.770	4.225	5.055

^aBelow detection limit**Table 4a: Concentration of metals for samples leached in basic medium (pH = 12)**

Sample number	Sample name	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
1.	Calculator (Brand "C _A ") plastic	0.023	BDL ^a	0.034	0.385	0.027	0.533	0.501	0.388
2.	Mobile phone (Brand "MP _C ") plastic	0.002	BDL ^a	2.133	0.527	0.014	0.683	0.363	0.554
3.	Video game (Brand "V _A ") plastic	0.016	BDL ^a	0.940	0.558	0.040	0.706	1.091	0.355
4.	Video game (Brand "V _B ") plastic	0.015	BDL ^a	0.217	0.547	0.031	0.596	1.022	0.661
5.	Radioset (Brand "R _A ") plastic	0.026	BDL ^a	0.674	0.631	0.038	0.840	0.423	0.495
6.	Laptop (Brand "L _A ") plastic	0.014	BDL ^a	0.195	0.186	0.027	0.494	0.492	0.162
7.	Laptop (Brand "L _B ") plastic	0.021	BDL ^a	1.373	0.490	0.027	0.863	0.488	0.725
8.	Walkman (Brand "W _A ") plastic	0.021	BDL ^a	1.503	1.344	0.038	0.683	0.432	0.583
9.	Mobile phone (Brand "MP _A ") PCB	0.022	BDL ^a	2.177	0.265	0.031	1.303	4.180	0.441
10.	Mobile phone (Brand "MP _B ") PCB	0.021	BDL ^a	2.720	0.291	0.067	1.829	3.530	0.426
11.	Mobile phone brand "MP _C " PCB	0.023	BDL ^a	3.633	0.328	0.080	1.539	4.278	0.786
12.	Laptop (Brand "L _A ") PCB	0.004	BDL ^a	3.485	0.317	0.054	2.379	4.088	0.638
13.	Laptop (Brand "L _B ") PCB	0.014	BDL ^a	3.645	0.280	0.040	1.829	4.230	0.561

^aBelow detection limit**Table 4b: Amount of metals for samples leached in basic medium (pH = 12)**

Sample number	Sample name	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
1.	Calculator (Brand "C _A ") plastic	0.460	BDL ^a	0.685	7.700	0.535	10.665	10.025	7.750
2.	Mobile phone (Brand "MP _C ") plastic	0.030	BDL ^a	42.665	10.530	2.700	13.650	7.265	11.070
3.	Video game (Brand "V _A ") plastic	0.310	BDL ^a	18.805	11.155	0.805	14.120	21.810	7.095
4.	Video game (Brand "V _B ") plastic	0.270	BDL ^a	4.345	10.945	0.615	11.920	20.430	13.220
5.	Radioset (Brand "R _A ") plastic	0.510	BDL ^a	13.470	12.625	0.765	16.790	8.460	9.985
6.	Laptop (Brand "L _A ") plastic	0.285	BDL ^a	3.900	3.720	0.535	9.880	9.840	3.245
7.	Laptop (Brand "L _B ") plastic	0.420	BDL ^a	27.450	9.795	0.535	17.265	9.750	14.500
8.	Walkman (Brand "W _A ") plastic	0.410	BDL ^a	30.055	26.870	0.765	13.650	8.645	11.660
9.	Mobile phone (Brand "MP _A ") PCB	0.445	BDL ^a	4.355	5.290	0.615	26.060	83.600	8.820
10.	Mobile phone (Brand "MP _B ") PCB	0.420	BDL ^a	54.400	5.815	1.335	36.585	70.600	8.525
11.	Mobile phone brand "MP _C " PCB	0.460	BDL ^a	72.650	6.550	1.600	30.770	85.550	15.720
12.	Laptop (Brand "L _A ") PCB	0.070	BDL ^a	69.700	6.340	1.070	47.580	81.750	12.755
13.	Laptop (Brand "L _B ") PCB	0.285	BDL ^a	72.900	5.605	0.805	36.585	84.600	11.220

^aBelow detection limit

The estimated relative Hazard Potential of different waste categories during landfilling has been listed in Table 5.

The values obtained for metal leaching were much less as compared to standard TCLP and scale-up TCLP. This could be attributed to the fact that instead of the extraction solution used in TCLP test, ultrapure water was used (with varying pH) for leaching. Extraction solution contained acetate ions that formed complex with lead and thus provided the worst leaching conditions. The values for lead were, however, comparable to the extractions with landfill leachates. Also, a normal filter paper (instead of glass fibre filter) was used.

Mobile phone (Brand “MP_A”) PCB and Laptop (Brand “L_A”) plastic were estimated to be the most hazardous and least hazardous items respectively based on leachate extracted by ultrapure water samples. Mobile phone (Brand “MP_C”) PCB and Video game (Brand “V_B”) plastic were estimated to be the most and the least hazardous item respectively based on leachate extracted by samples having pH=2. Mobile phone (Brand “MP_C”) PCB and Mobile phone (Brand “MP_C”) Plastic were observed to be the most and the least hazardous items respectively based on leachate extracted by samples having pH = 12. Thus, under all pH conditions, mobile phone PCBs were observed to have highest risk (relatively) and hence most hazardous to disposal in landfills.

Summary and Conclusions

In this study, a characterisation of e-waste was conducted to assess the relative hazard potential during landfilling by simulating the leaching conditions. Leaching was highest for pH 2 and pH 12 samples, and least for ultrapure water. Lead, copper and nickel leached in considerable amounts in almost all samples. It was therefore inferred that neutral medium caused the least amount of leaching and acidic medium the highest. So, landfills with pH close to 7 must be preferred for dumping e-waste (if dumping is inevitable). Plastics were observed to be safe for disposal in landfills.

The current study provides insight into the hazard posed by popular e-waste categories. As some of the issues related to electronic wastes are better understood and quantified, the findings could provide a basis for modelling different intervention options and predicting their effects.

The findings could be utilised to support efforts to arouse and enhance public awareness regarding environmental protection by publicity and education to guide consumer preferences to support products that are manufactured with and ultimately generate little hazardous or solid waste.

Table 5: Relative hazard potential of different waste categories during landfilling

S. No.	Item	Leachate extracted by ultrapure water samples		Leachate extracted by samples having pH = 2		Leachate extracted by samples having pH = 12	
		Relative risk	Normalised relative risk	Relative risk	Normalised relative risk	Relative risk	Normalised relative risk
1.	Calculator (Brand “C _A ”) plastic	443.06	6	1679.77	6	847.71	3
2.	Mobile phone (Brand “MP _C ”) plastic	460.04	7	1290.22	5	478.56	2
3.	Video game (Brand “V _A ”) plastic	590.13	9	310.15	1	1271.32	5
4.	Video game (Brand “V _B ”) plastic	160.31	2	44.38	0	1154.73	4
5.	Radioset (Brand “R _A ”) plastic	611.83	9	508.02	2	880.96	3
6.	Laptop (Brand “L _A ”) plastic	283.19	4	382.93	1	704.05	3
7.	Laptop (Brand “L _B ”) plastic	332.94	5	1303.50	5	887.77	3
8.	Walkman (Brand “W _A ”) plastic	510.77	7	698.13	3	808.75	3
9.	Mobile phone (Brand “MP _A ”) PCB	1092.37	16	4175.49	15	4062.80	15
10.	Mobile phone (Brand “MP _B ”) PCB	454.32	7	4291.48	16	3593.78	13
11.	Mobile phone brand “MP _C ” PCB	924.79	13	4441.03	16	4226.24	16
12.	Laptop (Brand “L _A ”) PCB	496.90	7	3861.78	14	3896.34	14
13.	Laptop (Brand “L _B ”) PCB	537.88	8	4206.99	15	4096.20	15

APPENDIX I

Environmental Protection Agency (EPA) (1992)

Method 1311: Toxicity Characteristic Leaching Procedure.

The Toxicity Characteristic Leaching Procedure is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphase wastes. This is usually used to determine if a waste may meet the definition of Environmental Protection Toxicity. The TCLP analysis simulates landfill conditions. Over time, water and other liquids percolate through landfills. The percolating liquid often reacts with the solid waste in the landfill, and may pose public and environmental health risks because of the contaminants it absorbs. The TCLP analysis determines which of the contaminants identified by the United States Environmental Protection Agency (EPA) are present in the leachate and their concentrations. This provides an environment for accelerated leaching and gives maximum amount leached. Actual leaching in landfills takes several years to complete. The standard guidelines provided are used for estimating the environmental risk imposed in landfills.

The solid waste is crushed to a size of about 9.5 mm and transferred to an extraction bottle.

Weight of extraction fluid = $[20 \times \% \text{solids} \times \text{weight of waste filtered}] / 100$

The solid with appropriate extraction fluid (determined on the basis of pH) is rotated in a rotator device at 30 rpm for 18 hours. Ambient temperature needs to be maintained at 23 degree Celsius. The liquid, thus, obtained is separated from solid using a glass fibre filter. This is the TCLP extract. The pH is recorded and metal aliquots must be acidified to a pH <2. This extract is acid-digested and analyzed for metal content in atomic absorption spectro photometer.

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