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Review Paper

E-Waste- A Challenge for Tomorrow

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Abstract

Industrialization and extraction of natural resources have resulted in large scale environmental contamination and pollution. Large amounts of toxic waste have been dispersed in thousands of contaminated sites spread across our nation. Thus, the risk to human and environmental health is rising. These pollutants belong to two main classes: inorganic and organic. E-waste is growing exponentially recent years because the markets in which these products are produced are also growing rapidly. The US-EPA has estimated a 5 to 10% increase in the generation of e-waste each year globally. Perhaps even more alarming is that only 5% of this amount is being recovered. E-waste problem is of global concern because of the nature of production and disposal of waste in a globalized world. The challenge is to develop innovative and cost-effective solutions to decontaminate polluted environments, to make them safe for human habitation and consumption, and to protect the functioning of the ecosystems which support life. Bioremediation approach is currently applied to remove contaminants from soil, groundwater, surface water, and sediments including air. These technologies have become attractive alternatives to conventional cleanup technologies due to relatively low capital costs and their inherently aesthetic nature. Therefore, these technologies need to be applied to decontaminate e-waste from the soil-water environment. The present article summarizes the hazardous effects of e-waste, Indian and global scenario and innovative bioremediation technologies to remove it from environment.

Keywords: E-waste, polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA), heavy metals.

Introduction

Over the past few decades, enormous quantities of industrial pollutants have been released into the environment. Solid waste management, which is already a massive task in India, is becoming more complicated by the invasion of e-waste, particularly computer waste. Electronic-waste (e-waste) represents electronic products including computers, printers, photocopy machines, television sets, mobile phones, and toys, which are made of sophisticated blends of plastics, metals, and other materials. It is an emerging problem because of the volumes of e-waste being generated and the content of both toxic and valuable materials in them. The fraction including iron, copper, aluminium, gold and other metals in e-waste is over 60%, while plastics account for about 30% and the hazardous pollutants comprise only about 2.70%[1]. Electronic devices form a complex mixture of materials and components, often containing several hundreds of different substances, many of which are toxic and create serious pollution upon disposal. These include heavy metals such as mercury, lead, cadmium, chromium and flame retardants such as polybrominated biphenyls (PBB) and polybrominated diphenylethers (PBDEs). Disposal of the e-wastes is an emerging global environmental issue, as these wastes have become one of the fastest growing waste types in the world. The recent investigations of workers involved in manufacturing the chips, he drives and circuit boards are reporting health problems. Even the workers who handle even e-waste as a scrap has health problems. The recycling and disposal of computer waste in these countries becomes a serious problem since their treatment methods remain rudimentary. Such activities pose grave environmental and health hazards; for example, the deterioration of local drinking water which can result in serious illnesses. The hazardousness of e-waste is well recognized, but the knowledge on these hazards and the resulting risks associated with different treatment options is currently fragmented. Current article gathers the data on componenets and hazardous substances of e -waste that are creating environmental pollution and human exposure to these chemicals, resulting adverse effects due to recycling, incineration and landfill disposal of e-waste. Current study is based on different hazardous components present in e-waste, current senerio of E waste generation. Methods which are available and risk associated with those methods have also been mentioned.

Different categories of E-waste

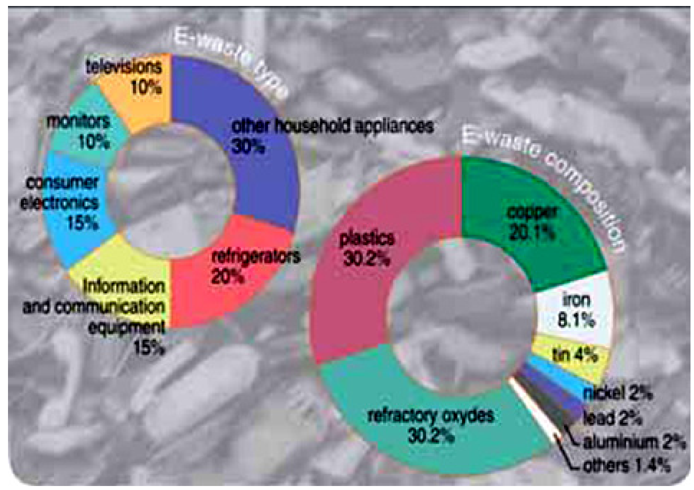
E-waste means electrical waste and electronic equipment, whole or in part included in, but not confined to equipment, scraps or rejects from their manufacturing process. E-waste is divided into different categories according to Environment Protection Act, 1986 (figure-1).

E-Waste: Types and Composition

Electrical and electronic equipment can contain a large number of hazardous substances, including heavy metals (e.g., mercury, cadmium, lead, etc.), flame retardants (e.g., pentabromophenol, polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA), etc.) and other substances (figure-2). Due to the presence of these substances, e-waste is generally considered as hazardous waste, which, if improperly managed, may pose significant human and environmental health risks.

Components of e-waste can be divided on the basis of their quantity; large, small and trace amounts. Substances found in large quantities include epoxy resins, fiberglass, PCBs, PVC (polyvinyl chlorides), thermosetting plastics, lead, tin, copper, silicon, beryllium, carbon, iron and aluminium. There are certain common components/parts of electrical and electronic appliances that contain the majority of the hazardous substances (figure-3).

Figure-1
Different Categories of E-Waste



Data source[2]: Basel Action Network, Sodhi & Reimer

Figure-2
Types of E-Waste

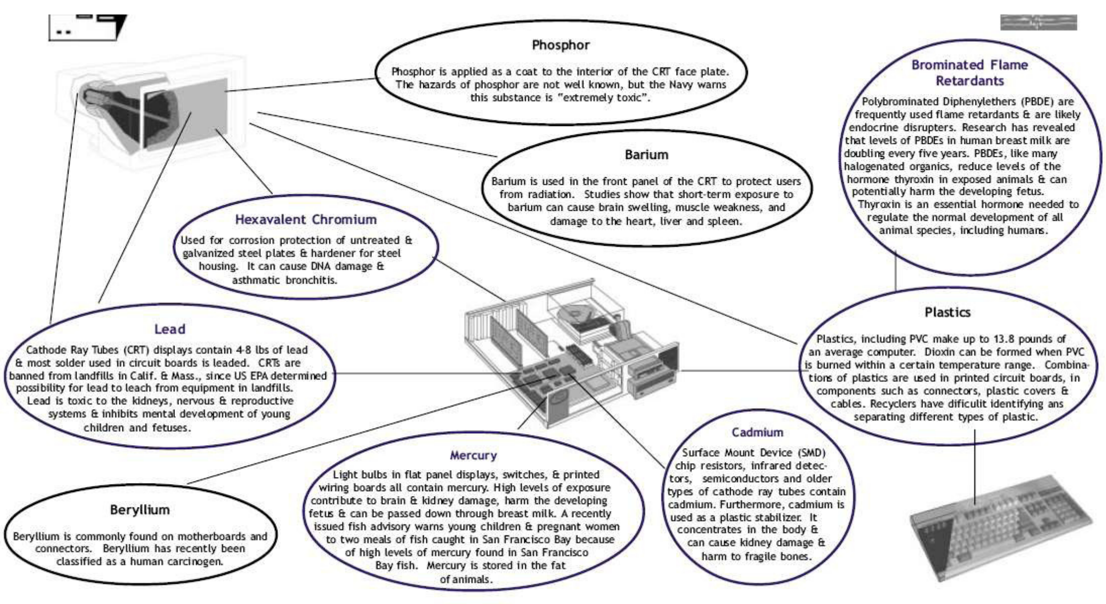


Figure-3
Hazardous Heavy Metals Associated with PC

Hazardous Components of E-Waste

Americium: one of the radioactive sources, known to be carcinogenic.

Mercury: Mainly found in fluorescent tubes (numerous applications), tilt switches (mechanical doorbells,thermostats), and flat screen monitors. It causes health effects such as; sensory impairment, dermatitis, memory loss, and muscle weakness. Environmental effects in animals include death, reduced fertility, slower growth and development.

Sulphur: Found in lead-acid batteries. Health effects include liver damage, kidney damage, heart damage, and eye and throat irritation. When released in to the environment, it can create sulphuric acid.

BFRs (Brominated flame retardants)**:** Used as flame retardants in plastics in most electronics includes PBBs, PBDE, DecaBDE, OctaBDE, PentaBDE. Health effects include impaired development of the nervous system, thyroid problems, and liver problems. Environmental effects: similar effects as in animals as humans. PBBs were banned from 1973-1977 on. PCBs were banned during the 1980's.

Cadmium: Found in light-sensitive resistors, corrosion-resistant alloys for marine and aviation environments and nickel-cadmium batteries. When not properly recycled it can leach into the soil, harming microorganisms and disrupting the soil ecosystem. Exposure is caused by proximity to hazardous waste sites and factories and workers in the metal refining industry. The inhalation of cadmium can cause severe damage to the lungs and is also known to cause kidney damage.

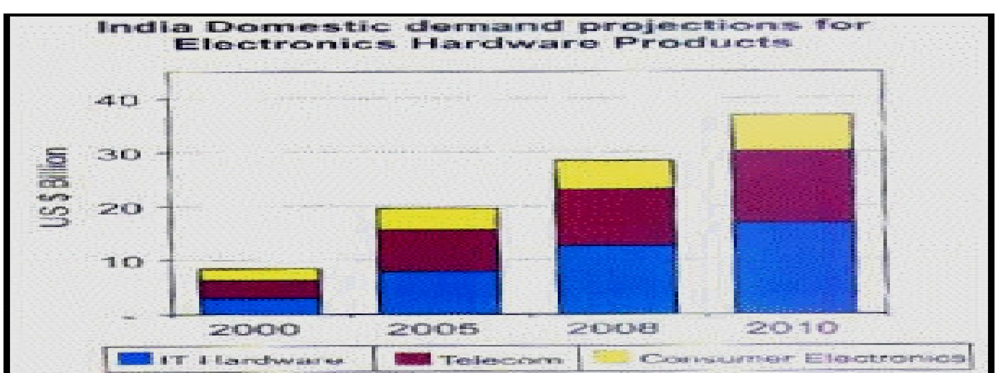
Lead: Found in CRT monitor glass,lead-acid batteries, some formulations of PVC. A typical 15-inch cathode ray tube may contain 1.5 pounds of lead but other CRTs have been estimated as having up to 8 pounds of lead.

Beryllium oxide: Commonly used as filler in some thermal interface materials such as thermal grease used on heatsinks for CPUs and power transistors,magnetrons, X-ray-transparent ceramic windows, heat transfer fins in vacuum tubes, and gas lasers.

Indian and Global Senario of E-Waste Generation

Indian Scenario: The growth rate of discarded electronic waste is high in India since it has emerged as an Information Technology giant and due to modernization of lifestyle. We are using electronic products for last 60 years; however, there is no proper disposal system followed in our country that has lead to enormous amount of e-waste (figure-4). There is a need to find proper disposal and recycling technique so that environmental pollution and health hazards can be reduced.

As there is no separate collection of e-waste in India, there is no clear data on the quantity generated and disposed of each year and the resulting extent of environmental risk. The preferred practice to get rid of obsolete electronic items in India is to get them in exchange from retailers when purchasing a new item. The business sector is estimated to account for 78% of all installed computers in India. Obsolete computers from the business sector are sold by auctions. Sometimes educational institutes or charitable institutions receive old computers for reuse. It is estimated that the total number of obsolete personal computers emanating each year from business and individual households in India will be around 1.38 million. According to a report of confederation of Indian industries, the total waste generated by obsolete or broken down electronic and electrical equipment in India has been estimated to be 1,46,000 tons per year[4]. The results of a field survey conducted in the Chennai, a metroplolitan city of India to assess the average usage and life of the personal computers (PCs), television (TV) and mobile phone showed that the average household usage of the PC ranges from 0.39 to 1.70 depending on the income class[5]. In the case of TV it varied from 1.07 to 1.78 and for mobile phones it varied from 0.88 to 1.70. The low-income households use the PC for 5.94 years, TV for 8.16 years and the mobile phones for 2.34 years while, the upper income class uses the PC for 3.21 years, TV for 5.13 years and mobile phones for 1.63 years. Although the per-capita waste production in India is still relatively small, the total absolute volume of wastes generated will be huge. The growth rate of the mobile phones (80%) is very high compared to that of PC (20%) and TV (18%)[6].



Source[6]: ENVIS Centre, Environment Department ,Government of Maharashtra, 2010.

Figure-4

Domestic Demans Projections for Electrical Hardware Products

Global Senerio: The EPA (Environmental Protection Act) estimates that 29.9 million desktops and 12 million laptops were discarded in 2007. That's over 112,000 computers discarded per day. The EPA report estimates that 31.9 computer monitors were discarded in 2007. In a 2006 report, the International Association of Electronics Recyclers projects that with the current growth and obsolescence rates of the various categories of consumer electronics, (a broader list than the EPA used above, including DVDs, VCRs, mainframes) somewhere in the neighborhood of 3 billion units will be scrapped during the rest of this decade, or an average of about 400 million units a year. According to the EPA, in 2008, 3.16 million tons of e-waste in the U.S. was generated and only 430,000 tons or 13.6 % of this amount was recycled. The rest was trashed in landfills or incinerators. The total e-waste increased from 3.01 million tons of e-waste generated in 2007, but the recovery rate stayed at 13.6%. Some 20 to 50 million metric tonnes of e-waste are generated worldwide every year, comprising more than 5% of all municipal solid waste. When the millions of computers purchased around the world every year (183 million in 2004) become obsolete they leave behind lead, cadmium, mercury and other hazardous wastes. In the US alone, some 14 to 20 million PCs are thrown out every year. In the EU the volume of e-waste is expected to increase by 3 to 5 per cent a year. Developing countries are expected to triple their output of e-waste by 2010. E waste is still the fastest growing municipal waste stream in the US.

Impact on Human Health and Environment

Electronic waste can come in many forms including computers, photocopiers, printers, faxes, monitors, batteries and mobile phones. E-waste contains significant quantities of toxic metals and chemicals. Electronic wastes can cause widespread environmental damage due to the use of toxic materialsin the manufacture of electronic goods[7]. Hazardous materials such as lead, mercury and hexavalent chromium in one form or the other are present in such wastes primarily consisting of Cathode ray tubes (CRTs), Printed board assemblies, Capacitors, Mercury switches and relays, Batteries, Liquid crystal displays (LCDs), Cartridges from photocopying machines, Selenium drums (photocopier) and Electrolytes. Although it is hardly known, e-waste contains toxic substances such as Lead and Cadmium in circuit boards; lead oxide and Cadmium in monitor Cathode Ray Tubes (CRTs); Mercury in switches and flat screen monitors; Cadmium in computer batteries; polychlorinated biphenyls (PCBs) in older capacitors and transformers; and brominated flame retardants on printed circuit boards, plastic casings, cables and polyvinyl chloride (PVC) cable insulation that releases highly toxic dioxins and furans when burned to retrieve Copper from the wires.All electronic equipments contain printed circuit boards which are hazardous because of their content of lead (in solder), brominated flame retardants (typically 5-10 % by weight) and antimony oxide, which is also present as a flame retardant (typically 1- 2% by weight).[8]

Nickel (Ni) which is present in E-waste causes skin damage, asthma, lung damage and carcinogen. It enters in environment throgh air. Antimony (Sb) causes skin irritation, hair loss, lung and heart damages and fertility problems. This element is better absorbed in soil containing steel,magnesium or aluminium.Poly brominated diphenyl ethers(PBDE) causes anemia damages skin,liver,stomach and thyroid, contamiante water and contaminate chain of production of some food. Tetra bromo bis phenol A(TBBPA) has some mutations and carcinogen effects. It causes damages to endocrine system. Poly brominatedbiphenyls (PBB) passes along with food chain damages kidneys liver and thyroid. Chliroflorocarbon (CFC) destroys ozone layer. Polyvinyl chloride (PVC) damages animal kidney and soluble in water and Arsenic is carcinogenic causes skin and lung cancer. Barium causes gastrointestinal disorder and muscle weakness, changes heart beat rate, paralysis and accumuate in aquatic system. Beryllium inhilation causes pneumonia, respiratory infllimation, lung cancer. Cadmium and Mercury are carcinogenic and causes lung damage. Therefore, a treatment technology needs to be developed for clean up of e-waste from the environment (table-1).

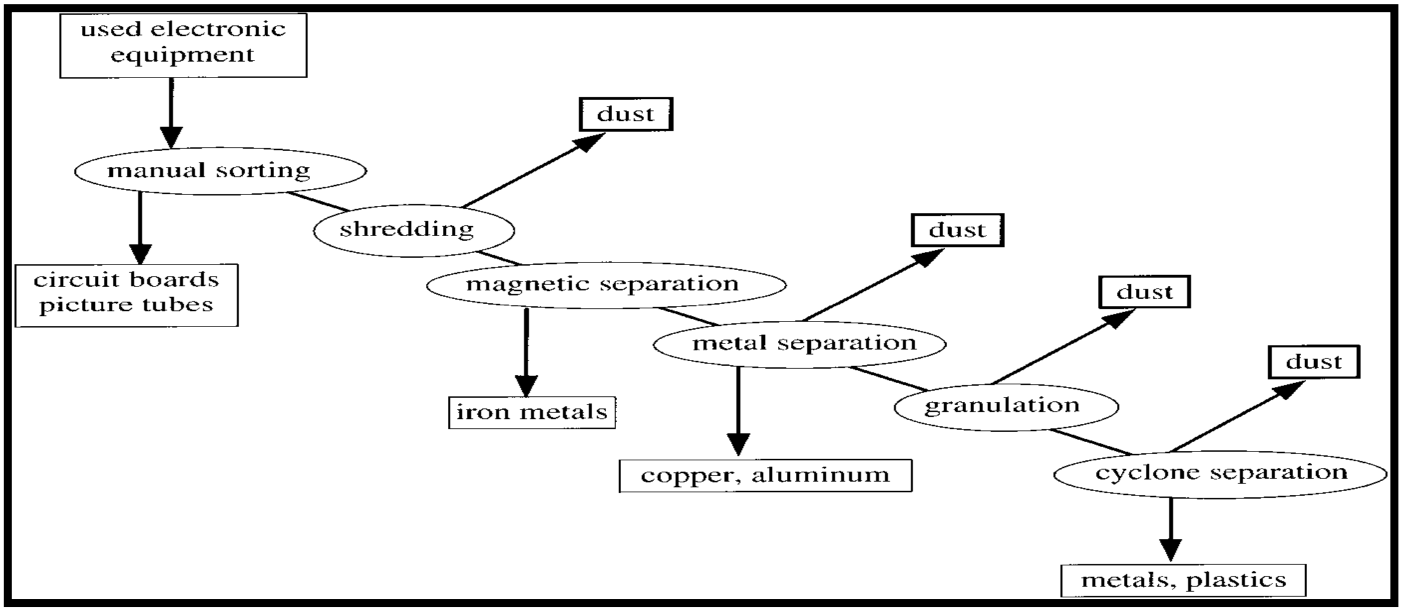
Treatment Techniques for E-Waste Management

Hazardous substances generated by E-waste are very harmful for environment as well as for humans. Therefore, an effective removal technique needs to be developed for clean-up of environment (figure-5). Following techniques are currently used for decontamination of environment from e-waste:

Table-1
E-Waste Toxins and Affected Body Parts

Components	Constituents	Affected body parts
Printed circuit boards	Lead and cadmium Berillium	Nervous system, kidney, lever
Motherboards	Lead oxide, barium and cadmium	Lungs, skin
Cathode ray tubes (CRTs)	Mercury	Heart, lever, muscles
Switches and flat-screen monitors	Cadmium	Brain, skin
Computer batteries	Polychlorinated biphenyls (PCBs)	Kidney, lever
Capacitors and transformers	Brominated flame-retardant casings cable	-
Printed circuit boards, plastic	Polyvinyl chloride	-
Cable insulation/coating Plastic housing	Bromine	Immune system

Source: Electronics For You, 2007.



Source[3]: Brandl et al. 2001

Figure-5

Schematic Treatment Process of Used Electronic Equipment

Landfilling: It is one of the most widely used methods for disposal of e-waste. In landfilling, trenches are made on the flat surfaces. Soil is excavated from the trenches and waste material is buried in it, which is covered by a thick layer of soil. Modern techniques like secure landfill are provided with some facilities like, impervious liner made up of plastic or clay, leachate collection basin that collects and transfer the leachate to wastewater treatment plant. The degradation processes in landfills are very complicated and run over a wide time span.

A study reported by Townsend et al. (1999), assessed the leachability of thirty-six CRTs using Toxic Characteristic Leaching Procedure (TCLP). Twenty-one of the thirty color CRTs exceeded the 5 mg/l of lead regulatory limit for characterization as a hazardous waste. The largest concentration of leachable lead came from the funnel portion of the CRTs at an average lead concentration of 75.3 mg/L. Based on the results, the authors called for inclusion of CRTs into regulatory programs targeting hazardous chemicals.[9]

In their another study, Townsend et al. (2004) tested 12 different types of electronic devices (CPUs, computer monitors, laptops,TV sets, printers, VCRs, cellular phones, remote controls, etc.). In many cases, lead concentrations in the leachates exceeded the regulatory limit of 5 mg/L and every device type leached lead above this level in at least one test. The authors concluded that the results provided sufficient evidence that discarded electronic devices that contain a color CRT or printer wiring boards with lead-bearing solder have a potential to be hazardous wastes for lead.[10]

Osako et al. showed the presence of BFRs in leachate from landfills in Japan. Higher concentrations of BFRs (PBDEs and TBBPA) were detected in the landfills that had crushed e-waste[11].

Recycling: Recycling involves dismantling i.e. removal of different parts of e-waste containing dangerous substances like, PCB, Hg, separation of plastic, removal of CRT, segregation of ferrous and non-ferrous metals and printed circuit boards. Monitors and CRT, keyboards, laptops, modems, telephone boards, hard drives, floppy drives, Compact disks, mobiles, fax machines, printers, CPUs, memory chips, connecting wires and cables can be recycled.

E-waste recycling is an emerging, evolving industry and, perhaps therefore, its hazards appear to have been overlooked so far. Hard data on emissions of the chemicals of concern in the indoor environment at e-waste recycling facilities are required in order to support risk assessment and establish industry specific guidelines (e.g., permissible workplace levels, occupational exposure limits, etc.) which seem to be lacking at present. The degree of hazard posed to workers and the environment, thus, varies greatly depending on the specifics of the individual facility operations. For example, some manual disassembly operations pose few health or environmental risks, while others that involve the breaking of CRTs or the use of shredders present a range of more serious concerns.The hazard associated with disassembly stage is the possibility of accidental releases and spillages of hazardous substances. For example, mercury, found within light sources (fluorescent tubes in scanners, photocopiers, etc.) as well as switches, could be released into the air of a recycling facility upon breakage of the shell[12]. CRTs present risk of implosion due to vacuum inside the tubes and inhalation hazard due to phosphor coating on the inner side of the CRT glass. There is scientific evidence that hazardous substances are released during shredding. In a US based electronics recycling facility, assessment of air quality in the vicinity of electronic waste shredders has shown cadmium and lead levels as high as 0.27 and 1.4 lg/m3, respectively.[13] The finding indicates that there was workplace contamination and a possibility of continuous exposure of workers to the toxic metals.

Similarly, Takigami et al. measured concentrations of BFRs, including PBDEs, TBBPA and hexabromocyclododecane (HBCD), and polybrominated dibenzo-p-dioxins/dibenzofurans (PBDDs/Fs) in the air of a TV recycling facility. All the chemicals were detected at concentrations higher than background levels. During the shredding process of TV housing cabinets, concentrations of the investigated brominated compounds were one to two orders of magnitude higher compared to the levels in the dismantling hall air.[14]

Incineration: It is a controlled and complete combustion process, in which the waste material is burned in specially designed incinerators at a high temperature (900-1000^{0}C). Advantage of incineration of e-waste is the reduction of waste volume and the utilization of the energy content of combustible materials. Some plants remove iron from the slag for recycling. By incineration some environmentally hazardous organic substances are converted into less hazardous compounds. Disadvantage of incineration are the emission to air of substances escaping flue gas cleaning and the large amount of residues from gas cleaning and combustion. E-waste incineration plants contribute significantly to the annual emissions of cadmium and mercury

Stewart and Lemieux conducted experiments on incineration of a mixture of personal computer motherboards, keyboards and cases using pilot-scale rotary kiln incinerator. The flue gas was analyzed for metals, halogens, volatile and semi-volatile organic products of incomplete combustion, including PCDDs/Fs. Measured metal emissions were significant, and consisted primarily of copper, lead, and antimony, while emissions of PCDDs/Fs were well below regulatory limits. Based on the results, Stewart and Lemieux suggested that incineration may be a viable option for electronics waste disposal, provided an appropriate particulate control device is used to control metal emissions.[15]

One study (Funcke and Hemminghaus, 1997) did observe the formation of PBDDs/Fs and PXDDs/Fs as a result of combustion of BFR-containing e-waste. The experiment involved combustion of municipal waste and co-combustion of municipal waste with e-waste. When BFR-containing e-waste was added, the quantity of PBDDs/Fs and PXDDs/Fs in the flue gas increased.[16]

Bioremediation Approaches for E-Waste

Bioremediation is a general concept that includes all those processes and actions that take place in order to biotransform an environment, already altered by contaminants, to its original status. Although the processes that can be used in order to achieve the desirable results vary, they still have the same principles; the use of microorganisms or their enzymes, that are either indigenous and are stimulated by the addition of nutrients or optimization of conditions, or are seeded into the soil. Biological techniques can increase the removal efficiency whereas thermal or physico-chemical methods alone are less successful, as shown in copper and gold mining where low-gradeores are biologically treated to obtain metal values, which are not accessible by conventional treatments. Over the years, many methods have been tested, used, approved or rejected. The most common, ineffective and inexpensive way to deal with polluted areas is to ignore deliberately their existence. Biotreatment is well accepted by industry as it goes along with the current popularity of maintaining nature’s harmony. Bioremediation has become a widely accepted option for the clean up of contaminated soils and aquifers although it does not have a fully credible reputation within the regulatory community.

There are numerous examples of employing bioremediation against various pollutants. Nowadays, there are four main biological techniques for treating soil and groundwater: (a) stimulation of the activity of indigenous microorganisms by the addition of nutrients, regulation of redox conditions, optimizing pH conditions, etc; (b) inoculation of the site by microorganisms with specific biotransforming abilities; (c) application of immobsilized enzymes; and (d) use of plants (phytoremediation) to remove and/or transform pollutants.[17] In the specific methods used for bioremediating contaminated soil and water, landfarming, composting, intrinsic bioremediation and slurry bioreactor are included.

Brandl et al.[18] done a research study in which microbiological processes were applied to mobilize metals from electronic waste materials. Bacteria-*Thiobacillus, thiooxidans*, *T. ferrooxidans* and fungi-*Aspergillus niger*, *Penicillium simplicissimum* were grown in the presence of electronic scrap. The formation of inorganic and organic acids caused the mobilization of metals. Initial experiments showed that microbial growth was inhibited when the concentration of scrap in the medium exceeded 10 g Ly1. However, after a prolonged adaptation time, fungi as well as bacteria grew also at concentrations of 100 g Ly1. Both fungal strains were able to mobilize Cu and Sn by 65%, and Al, Ni, Pb, and Zn by more than 95%. At scrap concentrations of 5–10 g Ly1, *Thiobacilli* were able to leach more than 90% of the available Cu, Zn, Ni, and Al. Pb precipitated as $PbSO_4$ while Sn precipitated probably as SnO. For a more efficient metal mobilization, a two-step leaching process is proposed where biomass growth is separated from metal leaching.

Phytoremediation for Electronic Waste

Phytoremediation might be a cost effective choice complementary to engineering based approaches. Phytoremediation is making use of vegetation for in situ treatment of soil, sediment, and water, which has been utilized successfully in sites contaminated by PCBs and other organic pollutants reaching 1.5 million tons.[18]

In one study Xiezhi[19], reported PCB removal, soil enzyme activities, and microbial community structures during the phytoremediation by alfalfa in field soils. Guiyu soils were grossly contaminated by PAHs, PCBs and deca-BDE. Concentrations of all PTS increased sharply in the same order of reservoir areas (RS) < rice fields (RF) < areas near burning sites (NOBS) < E-waste open burning sites (OBS). OBS soils had extremely high levels of total PCBs (73.8-1443 μg kg-1), PBDEs (2906-44373) and PCDD/Fs (30.0-968), which were the highest when compared with data available. NOBS were heavily contaminated by all PTS, with the concentrations 6-50 times of those in RS. This is the first detailed scientific investigation on PTS contamination in soil caused by open burning of E-waste. In the multi-component bioremediation system including PAH-degrading bacteria (*Acinetobacter sp.*), AMF (Glomus mosseae) and ryegrass (Lolium multiflorum), AMF significantly ($p<0.05$) improved the growth of ryegrass. Ryegrass cultivation improved growth of PAH-degrading bacteria and increased peroxidase activities in soil. Interactions of ryegrass with AMF or PAH-degrading bacteria significantly ($p<0.05$) accelerated the dissipation of PHE and PYR from soil. Using a rhizobox experiment, a decreasing dissipation gradient of PHE and PYR was revealed along radial direction of maize (Zea mays L.) root, with the highest dissipation rates in rhizosphere zone followed by near rhizosphere zone and bulk soil zone in outer compartments. The present results indicated that there is a potential for the development of a multi-component phytoremediation system for PAH contaminated soil, involving PAH-degrading bacteria, AMF and plant.

Lin et al. have reported enhanced phytoremediation potential of polychlorinated biphenyl contaminated soil from e-waste recycling area in the presence of randomly methylated-β-cyclodextrins. The study aimed to compare the phytoremediation potential of four plant species (rice, alfalfa, ryegrass and tall fescue) for PCBs contaminated soil from Taizhou city, one of the largest e-waste recycling centers in China. In addition, the enhanced effects of randomly methylated-β-cyclodextrins (RAMEB) on PCBs phytoremediation potential were evaluated. Higher PCBs removal percentages of 25.6–28.5% in rhizosphere soil were observed after 120 days, compared with those of the non-rhizosphere (10.4–16.9%) and unplanted controls (7.3%).

Conclusion

The current article summarizes that e-waste contains a number of hazardous substances. Heavy metals and halogenated compounds are of particular concern. Improper handling and management of e-waste during recycling and other end-of-life treatment options may develop potentially significant risks to both human health and the environment. Current simple recycling carried out in many developing countries is causing risks that could to a large extent, be avoided through the use of improved treatment methods. Biohydrometallurgical techniques allow metal cycling by processes similar to natural biogeochemical cycles. Using biological techniques, the recovery efficiency can be increased whereas thermal or physico-chemical methods alone are less successful, as shown in copper and gold mining where low-gradeores are biologically treated to obtain metal values, which are not accessible by conventional treatments. Bioremediation methods can improve scenario of current treatment practices available for e-waste. Besides, management practices for e-waste there is a need of doing more research in the area of bioremediation so that these techniques can be used for the treatment of E-waste.

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