Review Article

Waste Electrical and Electronic Equipment Disposal Problem in India, Routes of Disposal, Toxicology, and Impact on Human Health – A Narrative Review

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ABSTRACT

The increasing volume of waste electrical and electronic equipment (WEEE) discards poses significant environmental and health concerns globally, especially in developing countries like India. Despite regulatory efforts, improper WEEE disposal remains prevalent due to insufficient infrastructure, lack of awareness, and unorganized recycling practices. To address this challenge, we reviewed recent studies on WEEE management strategies in India, emphasizing effective implementation methods and innovative technologies. Our analysis revealed a need for strengthening formal collection networks, enhancing public participation through education campaigns, promoting circular economy principles, and integrating advanced sorting techniques into existing recycling processes. By synthesizing these insights, our review provides actionable recommendations for policymakers, industry stakeholders, and researchers working toward improved WEEE management in India.

Key words: Advanced sorting technology, circular economy, disposal, E-waste, India, policy recommendations, public engagement, waste electrical and electronic equipment waste

INTRODUCTION

Waste electrical and electronic equipment (WEEE) is a global problem created by the growing demand for popular consumer electronic appliances and industrialization. WEEE refers to electrical and electronic equipment which has become obsolete, equipment that has become defective beyond restoration, is too expensive to repair, or reached its end of life. WEEE disposal has important implications for the health of the population.

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PROBLEM STATEMENT

Country-wise contribution to global waste electrical and electronic equipment updated to 2013, visualized by the authors is shown in Figure 1. In 2022, India has become one of the top producers of WEEE in the whole world. Worldwide a staggering 57.4 million metric tons of e-waste was produced in the year 2021, of which around 17.4% is recycled.[1,2] The staggering growth of Indian waste electrical and electronic equipment production is shown in Figure 2. India has a very low e-waste recycling rate compared to global rates with

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estimates varying from 1% to 5% rates of recycling of WEEE. This is because, there is a deficiency of segregation mechanisms, a lack of industrial recycling facilities, and requires substantial manual manpower to safely recycle the WEEE. This WEEE contains valuable raw materials, metals which are lost if WEEE is not recycled. WEEE is completely non-biodegradable which means it cannot be disposed by composting. Intentionally or accidentally WEEE is dumped along with municipal solid waste, and this can lead to serious environmental pollution. Refrigerants used in air conditioning and refrigerators release carbon dioxide gas which contributes to global warming.[3]

The most common e-waste in India is broken, defunct mobile phones, followed by discarded computer parts, obsolete electrical equipment, medical equipment, and household electronic items such as refrigerators. Mumbai city tops in the production of e-waste, followed by Delhi and Bangalore cities. Safe disposal of the piling mountains of e-waste because of economic growth and development is a great challenge. In response, the Ministry of Environment, Government of India, has passed the 2016 E-waste (Management) Rules, 2016, which strictly regulates the management of WEEE in India and brings the process under the ambit of state pollution control board. This is especially important since the quantity of Indian WEEE production is projected to increase exponentially in the coming decade.[4]

E-waste contains over 1000 potentially harmful compounds, heavy metals, and bioactive organic polymers. Heavy metal exposure to silver (Ag) and nickel (Ni) is linked to a high risk of neurodegeneration, such as Alzheimer's disease. Exposure to furans and dioxins is linked to the development of cancers. Pregnant women and children are especially vulnerable to the noxious effects of the WEEE.[5]

WEEE MANAGEMENT PROBLEM PREVALENT IN INDIA

Most found WEEE in Indian refuse are broken, defunct mobile phones, followed by discarded computer parts, obsolete electrical equipment, medical equipment, and household electronic items, such as refrigerators. Mumbai city tops in the production of e-waste, followed by Delhi and Bangalore cities. Safe clearance of the accumulating mountains of e-waste because of economic growth and development is a great challenge. In response, the Ministry of Environment, the Indian Government passed the legislation in the year 2016 called E-waste (Management) Rules of 2016. This law strictly regulates the management of WEEE in India and brings the process under the ambit of the State Pollution Control Board. This is especially important since the quantity of Indian WEEE production is projected to increase exponentially in the coming decade.[6]

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MICROPLASTIC POLLUTION OF WATER BODIES

Recently, it has been discovered that microplastic pieces and microbeads, which are produced by mechanical shredding of plastic components for recycling, and used as exfoliative in shampoos is a substantial pollution of the water bodies and drinking water reservoirs of India. An average of 43,000 particles of plastic is found per square kilometers of water body, according to research published by the 5 Gyres Institute, in the US. Most of these plastic pieces are smaller than 1 mm in size and are designed to wash down the tubes of washbasins.

RECENT STUDIES FOCUSED ON THE ISSUE OF WEEE PROBLEM IN INDIA

There are several recent studies focused on the issue of WEEE disposal in India. Here is a brief summary of these studies:

- Bathurst *et al.* studied the effects of environmental exposure to lead on children's intelligence at the age of 7 years in the Port Pirie cohort study. Lead exposure was linked to sensory impairment, reproductive failures, fatigue, nausea, vomiting, diarrhea, damage to the kidneys, tremors, hair loss, and altered brain function.[6]
- Brigden *et al.* investigated the recycling of electronic wastes in China and India and reported workplace

and environmental contamination due to the presence of hazardous substances, such as lead, mercury, cadmium, and chromium.[7]

- Yañez *et al*. reviewed the problems faced by developing countries regarding human health and chemical mixtures, including those caused by WEEE.[8]
- Dutta *et al*. discussed how electronic waste pollution increased during the COVID-19 pandemic, causing severe consequences for public health and the environment.
- Chakraborty *et al*. examined the levels of dioxins and furans released during the recycling process of WEEE in dump sites across India.[9]
- Habib *et al*. developed a novel vibration system to recover valuable metals from WEEE. This approach could help reduce toxic emissions from traditional WEEE processing techniques.[10]

These studies emphasized the need for improved regulations and sustainable strategies for managing WEEE disposal in India to protect both public health and the environment.

CLASSIFICATION OF WEEE

WEEE has been broadly classified into three main categories which are as follows: (1) Large household appliances, such as washing machines, (2) Information technology and telecommunication devices, such as desktops, mobile phones, and laptops, and (3) Consumer electronics, such as liquid crystal display (LCD)/organic light emitting diode (OLED) televisions.[11]

ROUTES OF DISPOSAL OF WEEE

Three main routes of disposal of WEEE that is used by most of the countries are incineration, landfill, and recycling as shown in Figure 3.

INCINERATION

Most of the toxic molecules are emitted in smoke during incineration done at a lower temperature. Brominated/halogenated flame retardants which are commonly found in many electrical and electronic appliances, such as electrical circuit board laminates. These compounds are especially problematic and toxic. These brominated flame retardants and antimony trioxide are lifesaving in preventing electrical fires. Higher levels of polybrominated diphenyl ethers (PBDEs) were demonstrated in human breast milk in a pioneering study by Kim Hooper and Jianwen She. They were concerned that these PBDEs were fat soluble and were concentrated in the human body through a process called bioaccumulation, leading to secretion in breast milk.[12] PBDEs are released into the atmosphere by incineration and leaching from landfills. PBDE levels in humans are observed to be doubling every 2–5 years.

Polyvinyl chloride (PVC), a common component of wires and cases, evolves pungent, toxic chlorine, and subsequently hydrochloric acid. Hexabromocyclododecane is toxic and prohibited, except for the use of building insulation foams. Phosphorus also has flame-retardant properties; it produces char that stops the spread of fire. Phosphorus is also toxic and more expensive to use than brominated compounds. In addition, phosphorus-containing laminates are sensitive to moisture and suffer from the problem of faster degradation.[13]

The smoke from incineration of WEEE generates copious amounts of particulate matter that is largely composed of ash. This particulate smoke contains a substantial amount of heavy metal fumes such as cadmium, lead, zinc, and chromium. Heavy metals which are more volatile, such as cadmium and mercury, are immediately released in the flue gas, adsorbed in smoke particles. Hydrogen fluoride is produced from the burning of polytetrafluoroethylene plastic and PVC plastic produces hydrogen chloride gas. These may form sulfuric acid, hydrofluoric acid, and hydrochloric acid and adsorb on the surface of the particulate smoke. Acids are noxious and corrosive in nature.[14]

High melting and boiling point metals such as iron and copper are left in the bottom fly ash. In addition, some chemical processes such as chlorination and oxidation increase the volatility of metals, such as nickel and cadmium, causing them to raise in the flue gas. Dioxins and furans are carcinogenic, and pollutants are found in flue gas produced on WEEE incineration. Dioxins, are a family of highly toxic chemical compounds, are often produced as byproducts during the incineration of Waste Electrical and Electronic Equipment (WEEE). These compounds are part of a larger group of chemically-related pollutants known as persistent organic pollutants (POPs), which are notorious for their environmental persistence and potential for bioaccumulation. When WEEE, which includes discarded electronics and electrical appliances, is incinerated, the complex mixtures of plastics, metals, and other materials can produce dioxins through incomplete combustion and chemical reactions at high temperatures. These dioxins can be released into the atmosphere, subsequently settling onto soil and

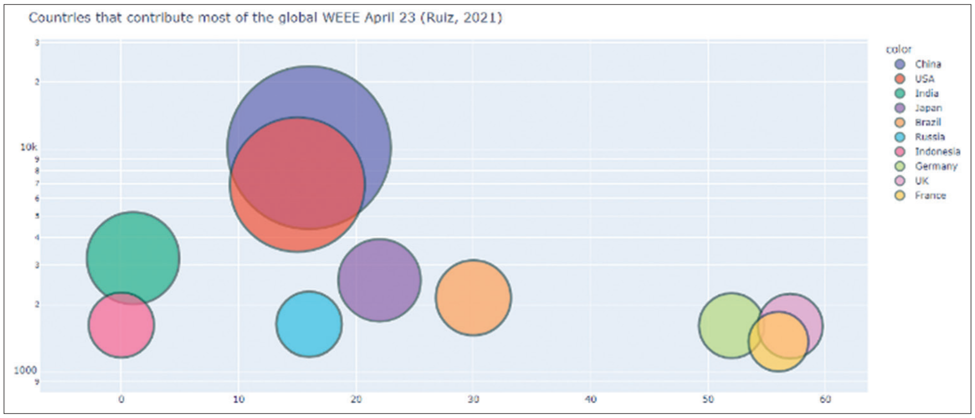

Figure 1: Country-wise contribution to global waste electrical and electronic equipment updated to 2013 (visualized by the authors, based on data)[3]

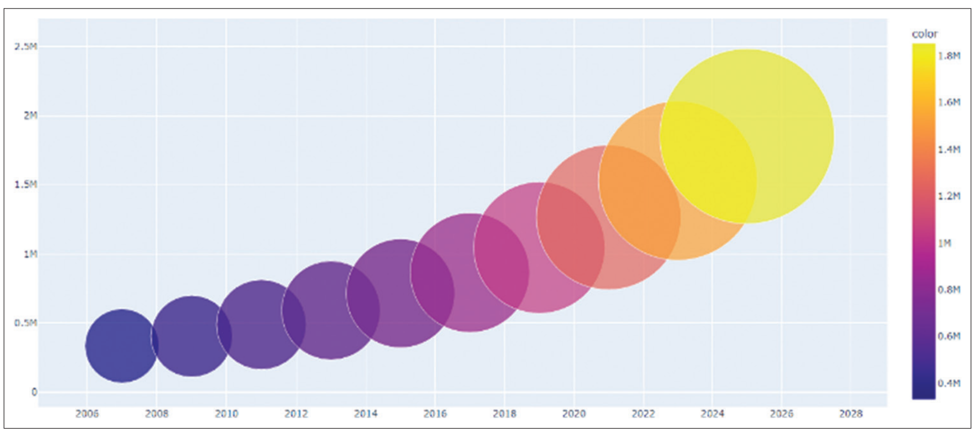

Figure 2: The staggering growth of Indian waste electrical and electronic equipment production, each bubble is to scale in units of metric tons (visualized by the authors, based on data)[2]

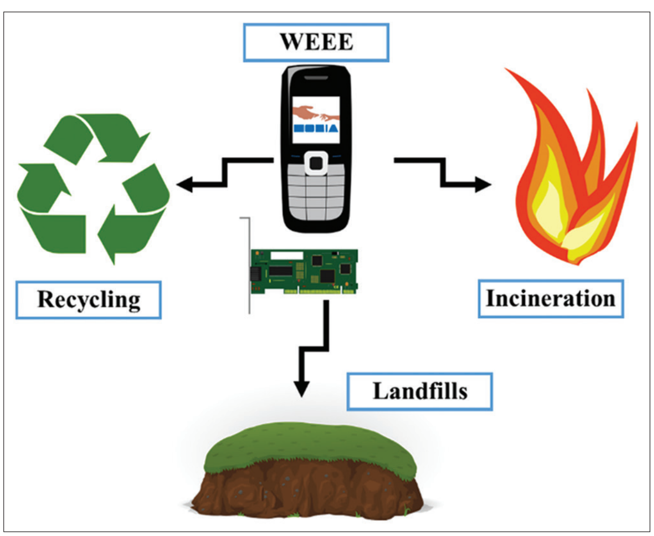

Figure 3: The three main routes of disposal of waste electrical and electronic equipment, namely incineration (burning), landfill (burying), and recycling (drawn by the authors)

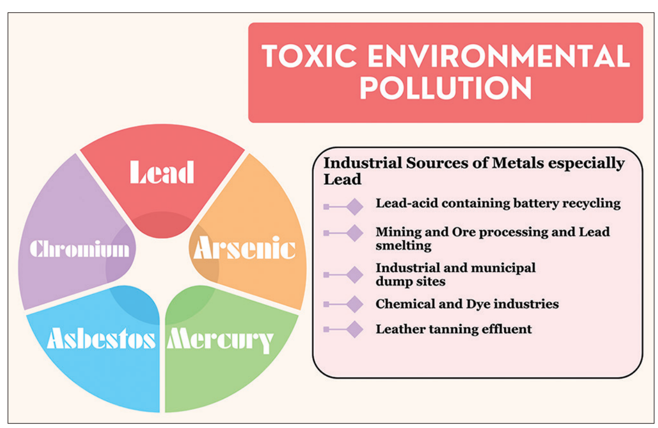

Figure 4: Toxic environmental pollution by heavy metals and industrial sources of heavy metals most commonly from waste electrical and electronic equipment (drawn by the authors).[30]

water bodies, leading to widespread environmental contamination. Dioxins are particularly concerning due to their severe health impacts, including carcinogenicity,

Table 1: Toxic effects of common heavy metals and their toxicity levels

Metal	**Biological effects**	
	Toxicity levels	**Clinical toxicity**
Lead	No lowest sage level toxic at all concentrations Minimum blood level is 5 $\mu g/dL$	Stomach pain or Lead colic, kidney damage, anemia, developmental delays, and brain damage, lead lines due to deposition in long bones, memory loss, high blood pressure, infertility, miscarriage, and nerve damage.
Cadmium	0.1 mg per cubic meter ($\mu g/m^3$) in air 2.5 $\mu g/L$ in portable water	Cancer, lung damage, bone damage, kidney damage, and vomiting. Headaches, hypertension, abdominal pain, anemia, and joint pain.
Mercury	Occupational Safety and Health Administration (OSHA) has set a permissible exposure limit (PEL) for mercury vapor of 0.1 mg/m^3 (100 $\mu g/m^3$) over an 8-h workday Environmental Protection Agency has set a maximum contaminant level for mercury in drinking water of 2 pp billion. Food and Drug Administration has set a guidance level for mercury in commercial fish and seafood of 1 ppm.	Severely affect to the kidneys, memory loss, developmental delays, and brain and tremors, swings in temperament (mad hatter), weakened muscles, vision issues, hearing loss, and numbness.
Chromium	Hexavalent chromium, the safe level is 0.02 $\mu g/m^3$ in air. 0.1 $\mu g/L$ in drinking water	Mutagenic, teratogenic, and carcinogenic Skin inflammation, liver/kidney damage, and lung cancer
Arsenic	0.01 mg/L in drinking water 0.1 $\mu g/m^3$ in air.	Developmentally toxic, neurotoxic, and carcinogenic Gastrointestinal problems, renal damage, respiratory conditions, and skin lesions
Manganese	0.15 mg/L in drinking water 5 $\mu g/m^3$ in air.	Parkinson's-like symptoms, developmental toxicity, and neurotoxicity liver damage, reproductive problems, and respiratory sickness Parkinson's-like symptoms, developmental toxicity, and neurotoxicity
Zinc	Exposure is 5,000 $\mu g/L$ in drinking water. 10 mg/m^3 in air.	Nausea, and neurotoxic effects reduced immunity, anemia, and copper deficiency

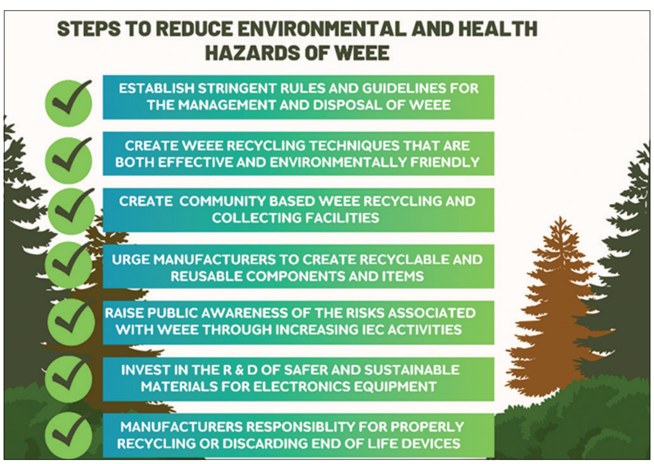

Figure 5: Suggestions to mitigate environmental and health hazards of waste electrical and electronic equipment (original illustration by the authors)[35]

endocrine disruption, and adverse effects on the immune and reproductive systems. The management and disposal of WEEE thus require stringent controls to minimize dioxin emissions and mitigate their harmful effects on both human health and the environment. Dioxins are potentially carcinogenic. These are produced when e-waste is incinerated and released into the atmosphere. Common municipal waste incineration is a significant source of air-borne dioxins.[15]

Finally, the residual fly ash is disposed by burying it in landfill sites, which can be subject to leaching. This leachate will have a high concentration of heavy metal and pollutes the environment and contaminates the groundwater.[16]

NEWER TECHNOLOGIES OF PYROLYSIS AND GASIFICATION

Pyrolysis/gasification uses high temperatures to break the bonds of the organic molecule and produce carbonaceous char or petrochemical compounds. These can be used be recycled or used for process energy. This requires a more complicated setup and expensive technology. Gasification is the process of reaction with oxygen in air and steam at high temperatures leading to complete oxidation and carbon dioxide gas formation. This process can be used only for organic molecules.[17]

LANDFILLS AND LEACHATES FROM LANDFILL SITES

A landfill is a waste management option of burying the waste and subjecting it to natural biodegradation. WEEE is not exactly biodegradable as they are made up of a lot of inorganic substances, such as metals. Landfills suffer from two main types of leaching and landfill gas.[18]

Leaching is because of water entry into a landfill, sometimes as rain or snow. A typical landfill design engineering attempts to minimize water entry into the landfill. Heavy metals, such as cadmium, lead, mercury, zinc, copper, chromium, and nickel, are often found in water leached out of landfills. Landfill gas is an effusion of methane and carbon dioxide gas, mixed with other organic compounds, which causes atmospheric pollution, and contributes to global warming. Landfill gas causes mucosal irritation of the nose and eye due to the presence of hydrogen sulfide (rotten-egg gas). The foul odor can be a source of distress for people and animals living near these landfill sites.[19] Toxic environmental pollution by leaching of heavy metals, most commonly from waste electrical and electronic equipment is shown in Figure 4.

The runoff of landfills contains a variety of toxic and polluting components. Landfill leachate can cause central nervous system effects due to neurotoxic, such as compounds dichloromethane and toluene, hepatotoxic compounds due to molecules, such as 1,l-dichloroethylene, and vinyl chloride and the potential for development of cancer due to carcinogenic 1,3-butadiene and aromatic compounds, such as benzene. The leachate often contains metals such as nickel, copper zinc, cadmium, lead, arsenic, and mercury. In addition, poisonous and carcinogenic polychlorinated biphenyls (PCBs), dioxins, and furans are found in liquid leachate.[19]

Research has found that there are risks of birth anomalies and reduced birth weight in babies born to humans living in the vicinity of landfills. Additional studies reported a rise in chromosomal defects in the proximity of landfills.[20]

RECYCLING

Recycling WEEE is an environmentally safe and sustainable alternative method of disposal. Unfortunately, this process also suffers from several problems. Recycling facilities manually sort and dismantle WEEE, this is an expensive, time-consuming process, takes substantial manpower, and takes a toll on the workers' health. The industrial recycling process usually comprises of following three steps: First, magnetic separators remove magnetic metal iron parts, second, eddy current separation using electric conductivity of non-ferrous metals, such as copper and aluminum is done, and third, plastic is floated or sifted out using water or air. Further, this segregated WEEE needs further industrial treatments like melting before it can be reused.[21]

Immediate problems in workers include main physical injury from WEEE, accidents, e.g., cuts (from broken cases and wires). Injuries resulting from contact with sharp edges of glass or metals in Waste Electrical and Electronic Equipment (WEEE) pose significant health risks to workers. These injuries can lead to infections or diseases such as tetanus, hepatitis B, and hepatitis C. Tetanus, caused by Clostridium tetani bacteria entering wounds, can result in severe muscle spasms and potentially fatal complications if left untreated. Hepatitis B and C viruses, transmitted through blood or bodily fluids, can cause chronic liver infections, potentially leading to liver cirrhosis or cancer.[21] Heavy metal exposure occurs in manual workers, prominently cadmium and mercury fumes from nickel-cadmium batteries. Studies have demonstrated that workers who are exposed to WEEE in the long-term suffer from gene defects, telomere shortening, impaired immune responsiveness, and increased oxidative stress in the body.[22]

PROBLEMS WITH DISPOSAL OF COMMON WEEE

Old cathode ray tube (CRT)-based televisions and monitors contain a toxic substance, such as lead, barium, phosphorous, and other heavy metals including cadmium and mercury. The amount of lead in CRT manufactured before 2006 is particularly alarming. Smashing the CRT monitor releases these dangerous chemicals directly into the environment. CRT monitors require a special method of safe dismantling and disposal, without spillage of toxic chemicals behind the glass. Fortunately, the CRT displays are almost phased out of India.[23]

LCDs are more environmentally friendly, and disposal is far safer than CRTs. These displays contain a layer of liquid crystal sandwiched between two electrodes, made up of transparent Indium-Tin oxide (ITO), and two polarizing filters. The next generation of organic light-emitting diode (OLED or organic LED) promises higher picture quality and clarity, lighter weight, and faster response time. On the other hand, OLEDs cannot be recycled unlike LCDS and suffer from degradation, moisture damage, higher power consumption, and screen flicker.[24]

A small proprietary liquid crystal is used in each LCD, about 0.6 mg/cm^2 of area, Recycling is the best option for disposing of LCDs though, often they are disposed by incinerating or burying them in the landfill. LCD incineration requires higher temperatures and can generate volatile, toxic molecules, such as dioxins and furans while landfilling can leach poisonous compounds into the environment.[25]

ITO electrode in LCD screens is made-up of silvery, rare element indium. Indium is a precious metal and has a limited natural reserve, making it an expensive and supply risk commodity. ITO is also used in capacitive touchscreens of mobile phones and tablets. It is a by-product of mining and extraction of metal zinc, around 55% of the total indium extracted is used to manufacture LCDs. The reduced zinc mining, demand from the LCD industry is constraining the reserves of indium. Technologies to recycle indium from LCDs are in active development.[26]

The proprietary liquid crystal found in LCDs is basically nontoxic and the manufacturers recommend disposal by incineration. These liquid crystals are irritants and do not biodegrade easily. The remaining, 70% of the glass found in LCDs can be recycled and reused.[27]

HEAVY METALS IN WEEE AND THEIR HEALTH HAZARDS

Three elements arsenic, lead, and mercury are described as poisonous heavy metals.

Heavy metals like cadmium are found in electroplated parts, nickel-cadmium batteries, CRT phosphors, semiconductors, pigments used to color plastic, and photodetectors. Mercury and hexavalent chromium salts are used as dope in semiconductor valves, and cadmium mercury telluride is used in infrared spectrometers and infrared telescopes. All forms of cadmium, inhaled, skin-contact, and consumed are toxic. Cadmium fume fever is a syndrome caused by exposure to fumes of cadmium, produced by the vaporization of cadmium due to incineration or welding. Welder presents with symptoms, such as pneumonia, with fever, cough, and chills. Long-term exposure ends up destroying the lung of the worker by causing progressive pulmonary fibrosis. Cadmium is also toxic to kidneys and may cause renal failure in workers. Cadmium is a well-known cancer-causing metal, listed under group 1 by the International Agency for Research against Cancer (IARC). Treatment is only supportive as there is no effective remedy for cadmium poisoning.[28]

Mercury is a liquid metal at room temperature and is a volatile substance. Mercury is a liquid metal at room temperature and has a high vapor pressure, making it a volatile and hazardous substance. Its ability to easily vaporize increases its toxicity, especially in the context of waste electrical and electronic equipment (WEEE). Exposure to mercury vapors can lead to severe health issues, emphasizing the need for careful handling and disposal of mercury-containing components in e-waste. This highlights the importance of proper recycling methods to mitigate environmental and health risks associated with mercury. Pure mercury is found in thermostats, thermocouples, sensors, relays, switches, medical equipment, such as thermometers, dental amalgams and blood pressure measuring devices, fluorescent lamps, and older mobile phone batteries. Mercury is still found in older CRT and button cells that power inexpensive toys and devices, such as LASER pointers. Mercury in the form of thimerosal used as a preservative in vaccines has been suspected to cause autism. In 1950, Japanese people belonging to the village of Minamata suffered from birth defects and neurological problems, due to bioaccumulation of methylmercury in sea-fish. The culprit was inorganic mercury in sewage dumped into the sea by a seashore factory, which was complexed to methylmercury by microscopic organisms. Methylmercury can transfer from the mother through the placenta and cause congenital anomalies in the fetus. Urinary mercury levels are a measure of inorganic mercury exposure.[29]

Acute inhalation causes pneumonia, and pulmonary edema, whereas ingestion of mercury, leads to acute renal failure from tubular necrosis, hemorrhagic gastroenteritis, and acute gingivostomatitis. Chronic exposure in WEEE workers presents with neurological damage and psychiatric manifestations. Fine intention tremors of the hands and face called Hatters' shakes. Depression and social withdrawal accompanied by episodes of anger called erethism. Acrodynia ("pink disease"), skin rashes, hearing impairment, speech impediment, visual disturbances, and dizziness/ataxia are also seen on exposure to organic mercury.[30]

Nickel exposure in acute settings, produces an allergic response, and chronic exposure increases the risk of lung cancer in workers. Soldered electronics lead and tin, the common electronic soldering process uses tin-lead-based solders in the ratio 60:40 that melt at around 183°C. These are significant health hazards due to large quantities of lead, hence are getting replaced in the industry by lead-free solders of tin-silver-copper solders (SAC alloys). Lead is a very toxic metal and chronic lead poisoning presents with abdominal pain, anemia, and neurological and renal problems. In children, it can lead to growth retardation or developmental delay. Muscle weakness due to the involvement of motor nerves, arthritis, and gout are also some of the symptoms of chronic lead poisoning. X-ray visible "lead lines" of deposition in long bones and measurement of whole blood lead concentration measure can be used for diagnosis. Treatment is by lead chelation using succimer, DMSA, and edetate calcium disodium (calcium-ethylenediaminetetraacetic acid). Exposure to large quantities of metal tin in WEEE workers leads to muscle weakness, tremors, seizures, hallucinations, and psychiatric problems.[31]

Trivalent chromium is largely nontoxic. Chromium metal is commonly used in electroplating and metal treatment. They confer abrasion resistance and protection against rust and corrosion. Chromium is added to steel parts, which are used outdoors and in high humidity environments, such as dams. Chromium, copper, magnesium, manganese, molybdenum, selenium, and zinc are essential metallic micronutrients in our diet. Occupational exposure to excessive chromium can lead to renal failure and skin lesions. A type of chromium-6 produced on stainless steel welding and heating is a known carcinogen leading to lung cancer in workers.[32] Table 1 depicts the toxic effects of common heavy metals and their toxicity levels.

TOXIC ORGANIC COMPOUNDS FROM WEEE DISPOSAL

Polycyclic aromatic hydrocarbons (PAHs) are products of the incineration process. PAH is local irritants and is linked with skin, pulmonary, and gastric cancers. Dioxins, furans, and PCBs are 75 similar chemicals, produced due to incineration. In the past, these were used as insulator fluids in heat exchangers and electrical transformers. These can lead to chloracne (an acne-like rash that occurs mainly on the face and trunk following acute exposure), liver problems, and elevated blood lipids. These are lipophilic meaning they are secreted in blood, and breast milk and accumulate in the body fat of the worker lead to chronic health problems. Studies on animals exposed to these chemicals demonstrate numerous diseases, such as cancer, endocrine imbalance, and reproductive problems.[33]

CONCLUSION AND FUTURE RECOMMENDATIONS

Proper management of WEEE requires a holistic approach, considering the environmental and health implications of disposing of WEEE.[34] The following measures will help India in managing WEEE: Community awareness about segregating WEEE, company legislations, training of workers involved in e-waste handling, inculcation of corporate responsibility to help in recycling the waste from their manufactured or imported products, development of a framework for acquisition and disposal of WEEE, regulation of landfill sites, incentives for industries and funds health risk assessment research, restriction on import of e-waste and proper maintenance of incinerators. Some of the suggestions to mitigate environmental and health hazards of waste electrical and electronic equipment are shown in Figure 5.

The inclusion of pollution prevention in development strategy frameworks and media coverage of pollution and information, communication, and educational activities in health-related domains can be done to increase the public cognizance of the issue of WEEE disposal, environmental pollution, and public health.

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