

# Biochemical hazards associated with unsafe disposal of electrical and electronic items

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## 3.1 Introduction

Many elements (some of them are relatively rare) are used in electronic and electrical instruments. [Table 3.1](#) shows some common elements that are found in many electrical and electronic instruments.

All these elements are not distributed uniformly in nature, but the table is useful in the general sense. Today mining activities are more carefully regulated worldwide but disposal and recycling are not.

Broadly speaking, all electrical and electronic items are made up of (1) electrically conducting or semiconducting functional part, (2) insulating stuff (mostly plastic or ceramic), and (3) enclosure meant for physical protection of the device (can be metal or plastic). At the end of service life, these parts may be segregated so that an efficient recycle can be attempted. It is most economical if the desired segregation is done at an early stage when the parts can be visually identified.

Many elements, compounds and polymers are commonly used in electrical and electronic industries. Every known element, compound, and molecules of biological origin have been assigned a number (this is not a number in the mathematical sense) by the American Chemical Society as a CAS (Chemical Abstracts Service) number that is unique. According to the official site maintained by the American Chemical Society, “CAS REGISTRY is the most authoritative collection of disclosed chemical substance information, containing more than 141 million organic and inorganic substances and 67 million sequences . . .” (<http://support.cas.org/content/chemical-substances/faqs>). Although this number is widely used all over the world, several other countries have their own system of classification (Beilstein is widely used in Germany). However, the CAS Registry Number is only a unique identifier and there may be several linked references present in the Registry. The toxicity data are maintained (in the United States) by the safety data sheets (SDS) [material safety data sheets (MSDS)] that is maintained by the Occupational Safety and Health Administration (OSHA) of the US government, Department of Labor. They use the CAS number as a reference to identify any given chemical. The basic objective is, simply stated, “The Hazard Communication Standard (HCS) (29 CFR

**Table 3.1** Abundance of common elements in Earth's crust (ppm).

Z	Symbol	Name	Abundance (ppm)	Comments
3	Li	Lithium	20	Less common alkali metal, used in modern cells
4	Be	Beryllium	2.0	Low density reactive metal, used in X-ray tubes
5	B	Boron	7.0	Toxic to insects and lower forms of life
13	Al	Aluminum	$80 \times 10^3$	Widely distributed, nontoxic
14	Si	Silicon	$270 \times 10^3$	One of the most common elements on earth
24	Cr	Chromium	96	Used in many ferrous alloys
25	Mn	Manganese	$1.0 \times 10^3$	Used in many ferrous alloys
26	Fe	Iron	$58 \times 10^3$	Widely distributed, nontoxic
27	Co	Cobalt	28	Less common iron group element
28	Ni	Nickel	72	Less common iron group element
29	Cu	Copper	58	Widely used in electrical and electronic items
30	Zn	Zinc	82	Widely used in batteries
31	Ga	Gallium	17	Used in LEDs
32	Ge	Germanium	1.3	Used in semiconductors, detectors
33	As	Arsenic	2.0	Used in semiconductors
34	Se	Selenium	$50 \times 10^{-3}$	Rare element; used in light detectors
42	Mo	Molybdenum	1.2	Used in tool steels
46	Pd	Palladium	$3 \times 10^{-3}$	Rare element; used as catalysts
47	Ag	Silver	0.08	Used in some solders
48	Cd	Cadmium	0.18	Used in some special cells
49	In	Indium	0.2	Used in semiconductors; soldering
50	Sn	Tin	1.5	Electroplating; soldering
51	Sb	Antimony	0.2	Special detectors
52	Te	Tellurium	X	special semiconductor detectors
53	I	Iodine	0.5	High energy detectors (gamma ray)
55	Cs	Cesium	1.6	Photosensitive detectors
74	W	Tungsten	1.0	Incandescent lamp filaments; crucibles
78	Pt	Platinum	X	Rare and precious metal; used in resistance sensors
79	Au	Gold	$2 \times 10^{-3}\dagger$	Rare and precious metal; contact surface plating
80	Hg	Mercury	$20 \times 10^{-3}\dagger$	Used in batteries; discharge lamps
81	Tl	Thallium	0.47	Used in gamma ray detectors
82	Pb	Lead	10	Most common solder; some special detector

(Continued)

**Table 3.1** (Continued)

Z	Symbol	Name	Abundance (ppm)	Comments
83	Bi	Bismuth	$4 \times 10^{-3}\ddagger$	Used in semiconductors; soldering
90	Th	Thorium	5.8	Used in vacuum tubes (not completely obsolete)
92	U	Uranium	1.6	Nuclear reactors (not common in electronics)

Abundances of the elements, <[http://www.kayelaby.npl.co.uk/chemistry/3\\_1/3\\_1\\_3.html](http://www.kayelaby.npl.co.uk/chemistry/3_1/3_1_3.html)> (accessed 29.04.18.). (The numbers above are average values suggesting that typical concentrations of the above elements in commercial ores are significantly higher than the numbers reported above. They are usually present in much smaller amounts in a typical habitable environment. Very few elements are uniformly distributed over the earth's surface). It has been suggested that urban dumps of electrical and electronic items may be practical source of several of the above elements (in particular, for rare and precious elements, e.g., Ag, Au, Pt, or Pd).

1910.1200(g)), revised in 2012, requires that the chemical manufacturer, distributor, or importer provide SDSs (formerly MSDSs or material safety data sheets) for each hazardous chemical to downstream users to communicate information on these hazards.” Although these rules and guidelines are specific to the United States, most countries use these guidelines provided in the SDS. The information available in the SDS is rather detailed and contains 16 sections: (1) identification, (2) hazard(s) identification, (3) composition/information on ingredients, (4) first-aid measures, (5) fire-fighting measures, (6) accidental release measures, (7) handling and storage, (8) exposure controls/personal protection, (9) physical and chemical properties, (10) stability and reactivity, (11) toxicological information, (12) ecological information (non-mandatory), (13) disposal considerations (non-mandatory), (14) transport information (non-mandatory), (15) regulatory information (non-mandatory), and (16) other information.

Safety requirements of various chemicals are often conveyed via pictograms in accordance with International Standards Organization (ISO) recommendations (e.g., ISO 7010 describes graphical symbols related to hazardous and safety related matters). In the United States, the practice is similar, but the picture is often supplemented with a minimal text. The department of transportation (in the United States) requires that all vehicles must have suitable stickers describing the nature of the substance being transported. European chemical bureau (ECB) also have several pictograms recommended for hazardous materials (vide infra Fig. 3.1).

## 3.2 Life cycle of various elements

None of the elements are uniformly distributed over the earth's surface. Many are locally concentrated and occur at specific places. If the concentration is suitable (economic value), the deposits are treated as ores and minerals are extracted by several physical and chemical processes. Some of the elements are associated with other elements (e.g., Zn and Cd; Se and Te) and are often separated at a later stage. The isolation is never perfect, and the process leaves a large amount



## Category:ECB hazard symbols



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European Chemicals Bureau (ECB), 67/548/EWG

**English:** The [hazard symbols](#) according to directive 67/548/EWG by the [European Chemicals Bureau](#).

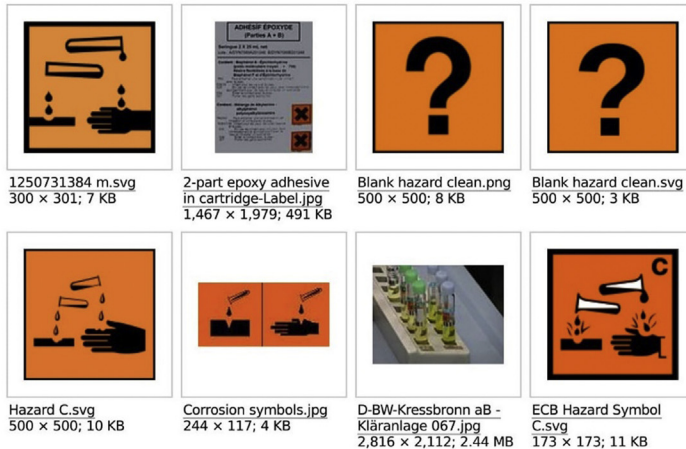
### Pages in category "ECB hazard symbols"

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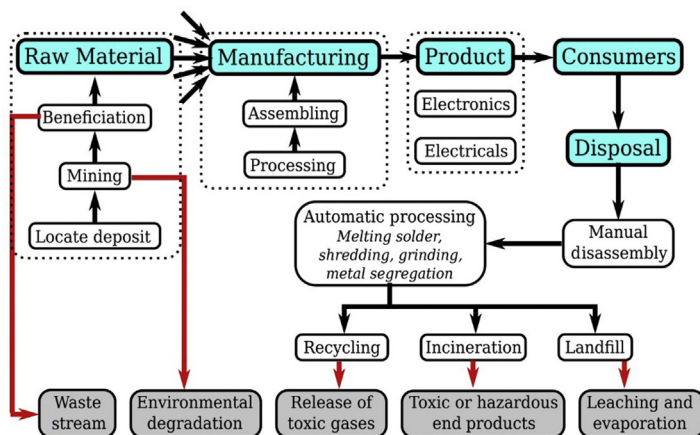
The following 57 files are in this category, out of 57 total.



**Figure 3.1** A selection of ECB recommended pictograms for hazardous materials.

*Source:* Adapted from Wikimedia Commons. The pictograms are expected to be self-explanatory.

of waste (that still contains the desired element but at a concentration that is economically unviable). Waste is produced both at the mining site and at the factory. Waste is a manufacturing by-product that can often be used for extraction of other elements (e.g., Cd is a by-product in Zn refining; Ag is often recovered during Pb and Cu refining). A large amount of waste is produced during this extraction phase and the effect on the environment is appreciable. At the end of the service life, most electronic and electric products are simply discarded (particularly if the item is physically small) but they still contain elements that can be economically reused. Such parts are often recycled [e.g., Cu and Au are often recovered from printed circuit boards removed from discarded electronic products; Cu, Al, and Fe are often removed from electric items for recycling]. The case (a case study) for the recycling of LCD TVs has also been reported in literature (Vanegas et al., 2017). The cycle can be schematically described in Fig. 3.2.



**Figure 3.2** Life cycle of common elements used in electrical and electronics. All the stages are energy intensive and produce large entropy. In modern electronics and electrical industry, recycling is relatively small.

### 3.3 Toxicity values and their significance

Toxicity values are meaningful for a particular molecular species; even the oxidation state may be important. Individual elemental composition may also be meaningful. For example, hydrogen, carbon, and nitrogen are not toxic by themselves but the molecule containing hydrogen, carbon, and nitrogen, hydrogen cyanide, is a highly toxic compound. For a species to be biochemically toxic, it must be able to seriously interfere with the metabolic (life cycle) processes. Toxicity often manifests at specific organs and the agent must reach the target organ to show its effect. Many toxic agents are themselves subject to metabolism and they are often made inactive after some time due to biochemical processing. For elements, they are most commonly present in their oxidized form ( $\text{Li}^+$  ion rather than Li metal) and similarly for the anions ( $\text{Cl}^-$  rather than gaseous  $\text{Cl}_2$ ). However, in the environment they can be transformed into different forms (microbial activity in the soil or geo-thermal effects over longer periods).

Toxicity of a molecule also depends on the specific route of administration. The same agent may be less toxic if administered orally rather than being injected. If the compound can be metabolized by the biochemical machinery, then the same dose administered over a period may be less toxic compared to the same being administered in one go. Many elements (e.g.,  $\text{Pb}^{+2}$  and  $\text{Hg}^{+2}$ ) cannot be efficiently processed and they tend to accumulate in specific organs. Often the elements form complex with other biomacromolecules and indirectly interfere with the metabolic subsystem. If the toxic compound is made insoluble, it shows much-reduced effect because of reduced bioavailability.

We often report the toxic effects in terms of lethal dose (LD50 being most common) but toxic effects can manifest in sublethal doses too. Therefore we also have

safe or permissible limits for various elements that are experimentally determined to have no observable side effects. Some of the toxic agents manifestly do not show short-term activity but effects can be seen over several generations.

Common metals like Fe, Al, Cu, Be, Mn, Ni, and Cr are used in electrical power transmission. They individually have different degrees of toxicity. Biochemical toxicity is dose-dependent and therefore it is relevant to know the relative proportions of toxic elements in electric and electronic items. Where ever available, we have attempted to provide the annual global production of the element and its overall share to the electric and electronic industries.

### **3.3.1 Biochemical toxicity of copper (Cu)**

Nineteen million tons of copper were produced in 2015 globally (Mineral Commodity Summaries 2017—Copper, <<https://minerals.usgs.gov/minerals/pubs/commodity/copper/mcs-2017-coppe.pdf>> accessed 29.04.18) and approximately 9% of this came from recycling. Therefore more than 90% (minus the growth) of the Cu produced annually is lost into the environment and is not recoverable. For power transmission, Al is steadily replacing Cu and 18% of the annual production of Cu is consumed by electrical and electronic industries. Electronic printed circuit boards are a major consumer of the metal. In 2015 the global sale value of printed circuit boards was USD 69.3 billion (contain both Cu and plastic) (sales worldwide 2010–18 <<https://www.statista.com/statistics/674137/printed-circuit-board-product-sales-value-worldwide/>>, accessed 29.04.18). Cu is an essential trace element required in both plants and animals for several enzymatic reactions as catalyst and cofactors. However, an excess of Cu can result in copper toxicity. The effect of environmental Cu on plants is more pronounced when compared to human and other mammals, as it is not readily bioaccumulated. Cu is relatively safe when compared to several other metals (cf. mercury, lead, and cadmium). In human, presence of excess Cu in system leads to production of metallothionein, which binds to Cu to form a water-soluble complex which can be eventually excreted. Further, the presence of organic and inorganic colloids in soil reduces Cu mobility and thereby the exposure of land plants to copper is reduced. However, aquatic plants are vulnerable to Cu toxicity. Studies indicate that Cu toxicity in plants depends on its bioavailability, which in turn is dependent on the physicochemical characteristics of the environment, such as pH, redox potential, soil and sediment type, water hardness, and organic content (Flemming and Trevors, 1989). Higher levels of Cu may result in inhibition of enzymes leading to interference in metabolic pathways. One of the major toxic effects on plants includes inhibition of chloroplast photosynthesis (Pádua et al., 2010). Excess of Cu leads to formation of hydroxyl radical, which initiate peroxidative chain reaction, thus degrading membrane lipids (Sandmann and Böger, 1980). Excess Cu inhibits overall vegetative growth in plants (Fernandes and Henriques, 1991). Aquatic species are vulnerable to copper toxicity about 10–100 folds more than mammals (Okocha and Adedeji, 2012).

As mentioned earlier, Cu is relatively safe for higher animals and studies on domesticated or laboratory animals showed a high tolerance limit of 300–800 µg/g

dry weight feed in diet. Cu being an essential trace element is supplemented in diet to fulfill dietary requirements. The maximum permitted levels of Cu in complete feed varies from animal to animal that also depends upon their age (metabolic activity). However, for farm animals, an optimum concentration of 20 mg/kg dry matter in total diet is recommended by Advisory Committee on Animal Feedingstuffs (ACAF), United Kingdom (Guidance Note for Supplementing Copper to Bovines <<https://acaf.food.gov.uk/sites/default/files/multimedia/pdfs/committee/guidancesuppcopperbovines.pdf>> accessed 29.04.18).

### 3.3.2 Biochemical toxicity of beryllium (Be)

United States is the single major producer of this rare element and produced 190 metric tons of Be in 2015 (with China a distinct second with 20 metric tons of production in the same year) out of the world production of 275 metric tons (Mineral Commodity Summaries 2016—Beryllium <<https://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2016-beryl.pdf>> accessed 29.04.18). Less than 10% of this came from recycling and most of the production went into copper-based alloys (Shah et al., 2016). Be–Cu alloy is widely used in many electrical and electronic devices. In plants, Be interferes with various physiological and morphological processes resulting in reduction the plant growth. Be significantly affects seed germination, biomass, and root length (Kaplan et al., 1990). The effect on various plants and the critical levels is reviewed by Shah et al. (Shah et al., 2016). It has been well documented that Be interferes with mineral uptake in plants and therefore growth and yield.

Individuals exposed to Be show increase in the total number of lymphocytes, however, there is no evident immune dysfunction as a result of short-term exposure to Be (Kim et al., 2013). A more severe effect of Be exposure is Berylliosis, or *chronic beryllium disease* (CBD), a chronic lung disease caused by sustained exposure to Be in genetically susceptible individuals. Noncaseating granulomas are formed as a result of aggregation of CD4<sup>+</sup> T-lymphocytes and macrophages following each instance of Be exposure and may ultimately lead to lung fibrosis. The effect of Be is attributed to its ability to induce posttranslational modification to create neo-antigens (Fontenot et al., 2016; Jakubowski and Palczyński, 2015; McCanlies et al., 2003).

The lowest observed adverse effect level for Be sensitization and CBD progression was suggested as 0.55 µg Be/m<sup>3</sup> (Kreiss et al., 1996). Further in 2005, Schuler et al. suggested the occupational exposure limits to be <0.2 µg/m<sup>3</sup> (Schuler et al., 2005).

### 3.3.3 Biochemical toxicity of manganese (Mn)

More than 17 million tons of Mn was produced in 2015 and about one-third of the metal came from South Africa. China is the second largest producer of this metal and it is poorly recycled because of lower volume of production. Most of the metal is used as a component of steel (Mn alloy—ferromanganese) but there are other



minor uses in electrical and electronic industries (most common being the resistance heating element in most electrical heaters). Unlike Al, Mn is found in several enzymes as a cofactor.

Mn is required for normal development and physiological processes both in plants and animals. It is critical to maintain Mn homeostasis, which is required for regulation of several enzymes as arginase, superoxide dismutase and glutamine synthetase. However, any imbalance in the Mn homeostasis leads to disease conditions. Mn deficiency has been shown to be linked to skin lesions and bone malformation (including osteoporosis), whereas an overexposure to Mn may lead to neurodegenerative diseases. Level of Mn in serum of healthy human individuals is indicated as 0.05–0.12  $\mu\text{g}/\text{dL}$  (Crossgrove and Zheng, 2004). The safe upper limit of Mn intake in humans is suggested to be 11 mg/day based on the study on Canadian women by Greger in 1998 (Greger, 1998), where the participants consumed 0.7–10.9 mg/day of Mn with no observable side effects and thus this was stated as the NOAEL (no observed adverse effect level). According to the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines 2013, the threshold limit value (TLV) as a time-weighted average (TWA) for respirable Mn particulate is restricted to 0.02  $\text{mg}/\text{m}^3$ , that is, an individual should not breathe more than 0.02  $\text{mg}/\text{m}^3$  of air of Mn over an 8-h work shift. The new recommended TLV-TWA for inhalable Mn (which may not be inhaled into deep lungs due to size) is 0.1  $\text{mg}/\text{m}^3$  (Revised TLV for Manganese <<http://www.lincolnelectric.com/en-us/education-center/welding-safety/Pages/revised-tlv-manganese.aspx>>, accessed 29.04.18). Manganism is a toxic condition resulting from chronic exposure to excessive levels of Mn.

### 3.3.4 Biochemical toxicity of chromium (Cr)

Chromium is only indirectly used in electrical and electronic industries as stainless steel in various forms. It is also used as an alloy in resistance heating elements. Cr plating is widely used (instead of Ni-plating) as an anticorrosion measure. In 2015 more than 30 million metric tons of Cr was produced worldwide with South Africa producing about half of the total. Cr is considered highly toxic and is a possible carcinogen.

Toxicity of Cr depends on the oxidation state, trivalent and hexavalent states being the most prevalent ones. Hexavalent chromium (Cr(VI)) compounds are powerful oxidizing agents and therefore more toxic compared to trivalent chromium. Further, Cr(III) compounds are poorly absorbed in the body, whereas Cr(VI) is absorbed by the lung and gastrointestinal tract (Wilbur et al., 2012).

### 3.3.5 Biochemical toxicity of aluminum (Al)

In 2015 the world production of Al was more than 51.5 million metric tons of which more than 50% was produced in China. The single major use of the metal is in transportation (body parts) but an 8% of the metal produced went to electrical industry (power conductor). (Mineral Commodity Summaries 2017—Aluminum



<<https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/mcs-2017-alumi.pdf>> accessed 29.04.18). Because of its lower cost (compared to Cu), Al has virtually displaced copper completely in power transmission applications. Al is highly recyclable and about 30% of the production comes from scrap (Global Aluminum Recycling <[http://www.world-aluminium.org/media/filer\\_public/2013/01/15/fi0000181.pdf](http://www.world-aluminium.org/media/filer_public/2013/01/15/fi0000181.pdf)>, accessed 29.04.18). The metal is highly reactive, but the exposed metal gets a thin oxide protective film that makes it less active and highly useful in diverse applications.

Al is not needed for life and is not an essential requirement for either plants or animals. The toxicity of Al depends mainly on the pH owing to its higher solubility in acidic environments. Mobilization of Al ions is facilitated by increasing acidification of the environment leading to toxic effects in living systems. Al interferes with the activity of metabolic enzymes as hexokinase, alkaline phosphatase, phosphodiesterase, and phosphoxidase, due to its high affinity to RNA and DNA. It is particularly harmful for nervous, osseous, and hematopoietic systems (Barabasz et al., 2002). Al exhibits both beneficial and detrimental effects on plants. On one hand, it stimulates iron absorption by the roots, negates the toxic effects of other metals as Cu and Mn and imparts protection against phytopathogenic fungi and adverse environmental conditions as drought and high soil salinity. On the other hand, Al toxicity may lead to inhibition of root growth. It hinders calcium uptake and translocation, induces oxidative stress and changes cell wall and plasma membrane properties and nutritional imbalance (Silva, 2012).

### **3.3.6 Biochemical toxicity of lead (Pb)**

About 5 million metric tons of Pb was produced in 2015 and the production of Pb is steadily but slowly decreasing because of its toxicity. Major part of the production goes into storage cells (lead acid batteries) and a significant part of the Pb present in storage cells is recycled. About 50% of the world production comes from China and the mining, production, and refining of Pb are associated with large scale environmental damages. Pb was earlier used as an antiknock compound [tetraethyl lead (TEL)] in petrol and it was transported into the atmosphere with the exhaust. Today the use of leaded (TEL) fuel has virtually stopped all over the world. Pb toxicity is often termed as lead poisoning due to the severe symptoms seen due to toxicity. They pose a range of effects on individuals exposed to Pb. However, the effects may vary depending on acute or chronic exposure. Acute toxicity may result in short-term effects as loss of appetite, headache, hypertension, abdominal pain, renal dysfunction, fatigue, sleeplessness, arthritis, hallucinations, and vertigo, whereas chronic exposure may lead to long-term effects including mental retardation, birth defects, psychosis, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis, muscular weakness, brain damage, kidney damage, and may even cause death (Jaishankar et al., 2014).

### **3.3.7 Biochemical toxicity of arsenic (As)**

Arsenic is used only in very small amounts in electronic (GaAs is used in Light Emitting Diodes) and electrical industries. In 2015 the value of global GaAs device

sales increased slightly to an estimated \$7 billion (Mineral Commodity Summaries 2018—Arsenic <<https://minerals.usgs.gov/minerals/pubs/commodity/arsenic/mcs-2017-arsen.pdf>>, accessed 29.04.18). World production of the element in 2015 was 36,500 metric tons and about 70% of this came from China. Both natural and anthropogenic sources cause As toxicity (water pollution being the most common). Elevated levels of As in the body leads to arsenic poisoning. A short-term exposure generally results in vomiting, abdominal pain, and diarrhea (Ratnaïke, 2003). However, chronic exposure results in arsenicosis [chronic arsenic toxicity (CAT)], usually caused due to the consumption of As contaminated ground water. CAT causes skin lesions like pigmentation, keratosis, pulmonary diseases, liver diseases like noncirrhotic portal fibrosis and other problems like neurological disorders, peripheral vascular disease, hypertension and ischemic heart disease, diabetes mellitus, nonpitting edema of feet/hands, weakness, and anemia; it is also associated with cancer of skin, lung, and urinary bladder (Mazumder, 2008).

Arsenate (As(V)) and arsenite (As(III)) are the two inorganic forms of arsenic (different oxidation states) that are easily taken up by root cells in plants. Arsenate is readily converted to arsenite, which is more toxic of the two forms. Arsenic causes oxidative stress in plants leading to membrane damage following lipid peroxidation. As(V) is an analog of inorganic phosphate and therefore is often easily transported by phosphate transporter proteins. Further, As(V) competes with phosphate during phosphorylation (glycolysis, oxidative phosphorylation), thus decreasing the cellular ability to produce ATP, and thereby hindering normal metabolism. As(III) is a dithiol reactive compound and binds to enzymes with closely spaced cysteine residues or dithiol cofactors and thus interfering with their native functionality (Finnegan and Chen, 2012).

### **3.3.8 Biochemical toxicity of lithium (Li)**

Lithium has been widely used in humans for treating mood disorders, but inadequate information about its adverse effects is still a concern. In 2015, 31,500 metric tons of Li was produced and 80% of the production came from Australia and Chile. A major part of the production goes into modern batteries (mobile phones are the major user). The element is not an essential trace element for plants or animals but because of the small size of the cation ( $\text{Li}^+$ ) it interferes with a number of metabolic processes. Commonly seen side effects include increased thirst, increased urination, and weakness. As the concentration of serum Li increases, toxicity increases. Serum concentration of <math><1.5 \text{ mEq/L}</math> is advised during the treatment phase. Early signs of Li toxicity may be seen at serum concentrations <math><2 \text{ mEq/L}</math>, such as diarrhea, vomiting, drowsiness, muscular weakness, and lack of coordination. Higher levels may result in giddiness, ataxia, blurred vision, tinnitus, and a large output of dilute urine, followed by damage to multiple organs and organ systems at levels above 3 mEq/L (Lithium salts monograph for professionals <<https://www.drugs.com/monograph/lithium-salts.html>>, accessed 29.04.18). Episodes of acute lithium toxicity were termed as the Syndrome of Irreversible Lithium-Effectuated Neurotoxicity, SILENT, with the most common symptom as persistent

cerebellar dysfunction (Munshi and Thamby, 2005). Depending on the concentration of Li in the growth medium, it can stimulate or inhibit plant growth. Li interferes with numerous physiological processes including photosynthesis, DNA biosynthesis, and enzyme metabolism leading to alteration in overall metabolism.

Discarded Li batteries are the major source of Li into soil, which leads to its entry in food chain (Shahzad et al., 2016). Because of the relatively low volume, the metal is poorly recycled. It is strongly recommended that the Li-cells from mobile (and other) devices should be collected and segregated for recycling. Li batteries are also used in passenger aircrafts and also in modern electric cars as auxiliary power source.

### **3.3.9 Biochemical toxicity of boron (B)**

Global production of boron was 9.4 million metric tons in 2015. Both borax and boric acids, two most important B compounds, are widely used in various industries (ceramics and detergents are the most important ones). Use of B in electrical and electronic industries is rather limited (used as a doping agent for Si semiconductors). Because of the low cost of the mineral, and the difficulty and cost of recovering, borates are rarely recycled. B is generally considered nontoxic to animals and humans, with LD50 at 6 g/kg body weight. A 4 g/day dose of boric acid was reported to be nontoxic; however, multiple doses of higher concentration are considered toxic. Boric acid is used as insecticide as it is more toxic to insects than to mammals. B is essential for plant growth, but excessive exposure to boron is toxic for plants. The initial symptoms include yellowing of leaves and may result in stunted growth. Growth inhibition in plants was seen with increased internal B concentration in the range of 1–5 mM across various plants. However, it was seen that mature cells in plants can withstand up to 60 mM of B for several days. This was further corroborating with a study in wheat, where rapid growth inhibition was observed when high B concentration was applied to the root tip but not when applied to mature root areas (Reid et al., 2004).

### **3.3.10 Biochemical toxicity of silicon (Si)**

Silicon is generally considered nontoxic in its natural forms, that is, silica and silicates. It is one of the most widely distributed elements on the earth's crust. In 2015, 7.6 million metric tons of elemental Si was produced worldwide. In 2013, 70,000 metric tons of Si was discharged into waste (in the production of thin slices of Si to produce photovoltaic solar cells, approximately 40% of the material is lost). It is estimated that by 2030, 6.3 million metric tons of Si waste will be produced and will be the largest consumer of elemental Si. A large fraction of the Si production went for several Fe (ferrosilicon) and Al alloys. Silicon carbide is also widely used as a commercial abrasive. Si dust has been shown to have adverse effects on lungs, but no significant toxicity is reported for limited exposure. Inhalation of large quantity of silicon dioxide (crystalline silica) can pose as a potent respiratory hazard

leading to silicosis. The LD50 of 3160 mg/kg body weight was obtained for crystalline silica when administered orally in rats (Lauwerys and Hoet, 2001).

Occupational exposure to crystalline silica has been attributed to several systemic autoimmune diseases, including scleroderma, rheumatoid arthritis, systemic lupus erythematosus, sarcoidosis, and some of the small vessel vasculitides with renal involvement (e.g., Wegener granulomatosis) (Parks et al., 1999). It can cause irritation in skin and eyes, when in contact, leading to redness and watering in eyes and skin inflammation. Si is known to stimulate plant growth and reduces heavy metal stress. It is the second most abundant element in the soil and is beneficial in reducing heavy metal stress both in plants and in soil. It acts by reducing active heavy metal ions present in the growth media, reducing metal uptake and stimulating antioxidant system in plants (Adrees et al., 2015).

### 3.3.11 Biochemical toxicity of iron (Fe)

Iron, because of its magnetic properties, is used in electrical motors, generators, and transformers. But the most important use, as steel, is to provide enclosure and support (construction industry is one of the major consumers). Because of the large volume of production (1.4 billion metric tons globally in 2015), the metal is widely recycled (as scrap).

Fe is essential for growth and development of most organisms, but high tissue concentrations can lead to physiological imbalance resulting in liver and heart diseases, certain cancers, and immune system dysfunction. Chronic inhalation of iron oxide fumes may result in siderosis and may increase the risk of lung cancer. Fe overload can lead to oxidative damage resulting in lipid peroxidation followed by membrane impairment, mainly in mitochondria and lysosomes. Excess of Fe can result in damage to various metabolic processes, most of which are downstream effects of oxidative stress caused by Fe overload (Britton et al., 2002). LD50 for iron in rats was reported as 30 g/kg (Iron—Chemical properties, health and environmental effects <<https://www.lenntech.com/periodic/elements/fe.htm>>, accessed 29.04.18).

### 3.3.12 Biochemical toxicity of cobalt (Co)

In 2015, 126,000 metric tons of cobalt was produced globally and half of this came from Congo (Mineral commodity Summaries 2017—Cobalt <<https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2017-cobal.pdf>>, accessed 29.04.18). Co is used in permanent magnets, superalloys, batteries, and in some chemical applications. Co is part of vitamin B<sub>12</sub> and is therefore beneficial for humans. Humans may be exposed to Co through air, water, or food. Breathing air containing high concentrations of Co can result in lung problems, such as asthma and pneumonia. High intake of Co can cause vomiting, nausea, neurological deficits (hearing and visual impairment), heart problems, and thyroid malfunctioning (Leyskens et al., 2017). Chronic exposure to Co may lead to considerable weight loss, dermatitis, and respiratory disorders. LD50 for cobalt when administered orally was found to

be 6171 mg/kg body weight. Plants grown on soil with high levels of Co may accumulate Co, which may be passed to human consuming those plant products. Co has been listed as possible carcinogen to human by International Agency for Research on Cancer (IARC) (Cobalt—chemical properties, health, and environmental effects <<https://www.lenntech.com/periodic/elements/co.htm>>, accessed 29.04.18).

### **3.3.13 Biochemical toxicity of nickel (Ni)**

Global production of Ni in 2015 was 2.3 million metric tons and Philippines is a major producer of the metal. The metal is widely used as a component of stainless steel (alloy), but a small part is used in consumer electronics in batteries. The metal is also a popular choice for electroplating (steel) to enhance corrosion resistance. The metal is widely recycled at the scrap level but active recovery from consumer items is low. Exposure of Ni to skin produces skin irritation; a further oral exposure may lead to erythema, eczema, and lichenification of the areas of skin in contact with Ni. Studies have indicated that Ni metal dusts and some Ni compounds are potent carcinogens, which may be due to facilitation of oxygen-free radical reactions by nickel oxides. The carcinogenicity of nickel compounds depends on their ability to enter cells and therefore water-soluble compounds exhibit less potency when compared to water-insoluble compounds (Cempel and Nikel, 2006).

High Ni concentrations in soil can hamper plant growth. Common symptoms of Ni toxicity in plants include chlorosis, necrosis, and wilting. It interferes with enzymatic activity of antioxidant enzymes such as superoxide dismutase and catalase, thereby enhancing oxidative stress. It interferes with significant processes such as photosynthesis, respiration, germination, and chlorophyll synthesis (Bhalerao et al., 2015).

### **3.3.14 Biochemical toxicity of zinc (Zn)**

Zinc is a widely used metal and the world production in 2015 was 12.8 million metric tons and China is a major supplier. Zn is widely used in several nonferrous alloys (e.g., brass), paints, and disposable batteries. Zn is an essential trace metal and is present in several enzymes as cofactors. Zn when taken orally in high concentration may lead to symptoms such as nausea, vomiting, epigastric pain, lethargy, and fatigue. Metabolically, Zn may interfere with copper and iron utilization and may negatively affect blood lipoprotein levels and cholesterol concentrations. US Recommended Dietary Allowance is 15 mg Zn/day; however, a much higher concentration close to 10 times the US RDA has been used for therapeutic purposes with no adverse effects (Fosmire, 1990).

### **3.3.15 Biochemical toxicity of gallium (Ga)**

Gallium is a relatively rare metal and the 2015 production was 470 metric tons (produced as a by-product during Al mining) and most of it was used by the semiconductor industry. Ga is used in LEDs and related optoelectronic devices and

some specialized integrated circuits. Ga is present in body in very trace amounts and is not considered to be toxic or carcinogenic. A case of accidental exposure to gallium halide resulted in dermatitis initially, followed by severe episodes of tachycardia, tremors, dyspnea, vertigo, and unexpected blackouts (Ivanoff et al., 2012). Acute exposure to gallium chloride can result in throat irritation and chest pain, and fume inhalation can be dangerous causing pulmonary edema and partial paralysis. Because of the low volume, Ga is not recycled from electronic devices.

### **3.3.16 Biochemical toxicity of germanium (Ge)**

Germanium is another element that is widely used in semiconductor industry and the world production in 2015 was 165 metric tons (China is again the major producer). The metal is extracted as a by-product in Zn, Cu, or Pb refining. Use of Ge in semiconductor devices is steadily decreasing (being replaced by Si) but the Ge is also used in optical fibers (and production of optical fibers is steadily increasing). Ge is also used in specialized detectors (GeLi and SiLi detectors) and some optical devices. The amount present in consumer items is small and hence the element is not recycled from electronic and electric devices. It is not a requirement for living systems. Intake of inorganic Ge preparations for a long time has been shown to negatively affect renal functions and cause gastrointestinal symptoms as vomiting, anorexia, and weight loss. Kidney damage was shown by tubular degeneration and interstitial fibrosis with minor glomerular abnormalities (Obara et al., 1991).

Another report has indicated that prolonged intake of Ge products has resulted in renal failure and may lead to death. Ge overdose can also cause anemia, muscle weakness, peripheral neuropathy, and myopathy (Tao and Bolger, 1997).

### **3.3.17 Biochemical toxicity of selenium (Se)**

Annual global production of Se is about 2000 metric tons and a major part of it is used by the glass industry. It is usually obtained as a by-product during Cu refining. About 12% of the total production is used in the electronics industry, mostly as a photosensitive element. CdSe is also used in IR devices. Se is essential as a trace element for growth (both plants and animals) but higher concentrations are toxic. Selenosis is caused by chronic exposure to selenium and the adverse effects of Se range from brittle hair and deformed nails, to even death in severe cases (Yang et al., 1983). A chronic Se poisoning is characterized by changes in the appearance of the nails and the early effects include brittle nails with longitudinal streaks and severe poisoning is indicated by breakage in nails, followed by regrown deformed nails or nails lost repeatedly. Overexposure to Se fumes may lead to garlic breath, conjunctivitis, vomiting, abdominal pain, diarrhea, and enlarged liver. Symptoms of acute toxicity include hypotension and tachycardia. It can also cause cardiac abnormalities and further leading to refractory hypotension from peripheral vasodilatation and direct myocardial depression leading to death (Nuttall, 2006). There may be serious symptoms as pulmonary edema or other neurological symptoms as tremor, muscle spasms, restlessness, confusion, delirium, and coma. Excessive

accumulation of selenium in plants can induce oxidative stress and can lead to distorted protein structure and function (Gupta and Gupta, 2017).

### 3.3.18 Biochemical toxicity of molybdenum (Mo)

In 2000 the world production of Mo was 129,000 metric tons. The major use is in metallurgy (ferromolybdenum used for alloying for special steels) and in chemical form in other industries ( $\text{MoS}_2$  is a popular lubricant). Its use in electrical and electronic industries is rather limited (used in some resistance heater elements). It is an essential trace element for both animals and plants and is a cofactor for some enzymes (nitrate reductase; xanthine dehydrogenase) but can be toxic at higher dose. In experiments conducted on rodents, reproduction and fetal development were critically affected at a concentration of 10 mg/L or higher, resulting in delayed fetal development (Fungwe et al., 1990; Vyskocil and Viau, 1999). The recommended dietary allowances for Mo were fixed at 4.45  $\mu\text{g}/\text{kg}$  per day for infants, 1.95–5.36  $\mu\text{g}/\text{kg}$  per day for children and 1.5–3.6  $\mu\text{g}/\text{kg}$  per day for adults (Vyskocil and Viau, 1999). Molybdenum is applied to the soil as a micronutrient often mixed with fertilizers. Mo exhibits little to no toxicity to *Isochrysis galbana*, a tropical microalga (Trenfield et al., 2015).

### 3.3.19 Biochemical toxicity of palladium (Pd)

In 2015, 216 metric tons of Pd was mined worldwide. The major use of the platinum group elements (Pt, Pd, Rh, Ru, Ir, Os) are as catalysts and automobile industry is one of the major users (Pd is preferred because it is the cheapest). Pd is used in the making printed circuit boards (plated through holes) but the amount used is rather small. It is mostly recycled from the automobile catalytic converters. All the platinum group elements are relatively inert (they are also rare) and they do not pose significant threat to the environment. Pd is known to inhibit enzymes such as creatine kinase, aldolase, succinate dehydrogenase, carbonic anhydrase, alkaline phosphatase, and prolidyl hydroxylase (Liu et al., 1979). Pd toxicity majorly affects mitochondria, it increases ROS production in mitochondria, collapses mitochondrial membrane potential, causes a negative effect on mitochondrial respiratory system that may lead to apoptosis (Hosseini et al., 2016). Another study on rats indicated that inorganic Pd compound can significantly induce drop in diastolic and mean blood pressure and a decrease in heart rate. However, Pd bound in an organic compound does not show any significant cardiotoxicity in isolated rat hearts (Peric et al., 2012).

### 3.3.20 Biochemical toxicity of silver (Ag)

The annual global production of silver is 27,000 metric tons, Mexico being the major supplier. Ag is also obtained as a by-product in the refining of Pb, Cu, and Au. It is widely used in several electrical and electronic industries. It is also used in chemical industries and photographic films. Ag is not a normal trace metal



(micronutrient) needed for animal or plant life. Ag is toxic and the TLV for metallic silver and soluble Ag compounds was fixed at 0.1 and 0.01 mg/m<sup>3</sup>, respectively, by ACGIH. The recommended exposure limit (REL) established by the National Institute for Occupational Safety and Health (NIOSH) is set at 0.01 mg/m<sup>3</sup> for all forms of Ag (Drake and Hazelwood, 2005).

The commonly known adverse effect of prolonged exposure to Ag is irreversible pigmentation of the eyes (argyrosis) or skin (argyria), resulting in bluish-gray pigmentation of the affected area. Other toxic effects of Ag include damage to liver and kidneys, irritation in eyes, skin, throat, or lungs. Chronic overexposure may lead to cardiac abnormalities, anemia, and permanent damage to nervous system (Drake and Hazelwood, 2005).

### 3.3.21 Biochemical toxicity of cadmium (Cd)

In 2015, 23,200 metric tons of Cd were mined worldwide (China is the largest producer of the metal). Cd is mainly used in rechargeable batteries (NiCd cells), paints and pigments, electroplating for corrosion resistance, and in chemical industries. Cd is a nonessential element (it is not present in living systems and is not required). Cd is considered toxic and prolonged exposure can affect multiple organs such as skeletal, urinary, reproductive, cardiovascular, central and peripheral nervous, and respiratory systems. Cd interferes with several physiological processes such as cell proliferation, differentiation, and apoptosis (Rani et al., 2014). It causes oxidative stress by inhibiting activity of antioxidant enzymes such as catalase, manganese-superoxide dismutase, and copper/zinc-dismutase. Cd is reported as a potent carcinogen (Rahimzadeh et al., 2017). It tends to accumulate in kidneys and affects excretory mechanisms.

### 3.3.22 Biochemical toxicity of tin (Sn)

Two hundred and eighty-nine thousand tons of Sn were produced globally in 2015 and China was the single largest producer of the metal. The metal is used as a protective layer (tin plating) to improve corrosion resistance, in chemical industries (organo-tin as a reagent in various chemical synthesis), and also as an alloy component in solder (with or without Pb; current trend is to use lead-free solder in all electronic applications). Sn is not an essential element for life and is considered nontoxic. *The Provisional Tolerable Weekly Intake for tin is 14 mg/kg body weight and recommended maximum permissible levels of tin in food are typically 250 mg/kg (200 mg/kg United Kingdom) for solid foods and 150 mg/kg for beverages (Blunden and Wallace, 2003).* Higher levels of Sn may accumulate in liver, bone, lymph nodes, and kidneys. Chronic exposure to Sn can cause liver damage, immune disorder, depression, and brain damage (Torack et al., 1960; Winship, 1988). Acute effects of tin overexposure include nausea, dizziness, diarrhea, eye and skin irritations, headaches, stomach aches, and breathlessness (Winship, 1988). The toxic effects of Sn can be attributed to its interaction with the absorption and excretion of Fe, Cu, and Zn (Westrum and Thomassen, 2002).

### **3.3.23 Biochemical toxicity of antimony (Sb)**

In 2015, 142,000 metric tons of Sb were mined globally, and China is the single major producer (77% of the world production). Sb is used as (1) an alloy in lead acid batteries (used widely in transport vehicles) and (2) in paints and chemicals, and also as (3) a flame retardant. The metal is highly toxic and attempts are being made to find less toxic substitutes. Chronic exposure to Sb in the air at levels of  $9 \text{ mg/m}^3$  may cause irritation of the eyes, skin, and lungs. Long-term inhalation of Sb can potentiate pneumoconiosis, altered electrocardiograms, stomach pain, diarrhea, vomiting, and stomach ulcers (Cooper and Harrison, 2009). Sb overexposure has been shown to cause adverse effects on respiratory, cardiovascular, gastrointestinal, and reproductive system (Sundar and Chakravarty, 2010). Sb has not been established as a carcinogen for humans but has been shown to cause lung tumors in rats. It is classified as a possible carcinogen by the IARC.

### **3.3.24 Biochemical toxicity of tellurium (Te)**

Global annual production of Te is about 220 metric tons and, like Se, is obtained as a by-product during Cu refining. Most of the Te is used for alloying and a small amount is used in electronics (special detectors; also in thermoelectric devices). Studies to identify Te effect on transformed and nontransformed cells indicate cytotoxic effects (Vij and Hardej, 2012). When inhaled, body converts Te to dimethyltelluride,  $(\text{CH}_3)_2\text{Te}$ , which produces pungent-smelling garlic-like odor, termed as “tellurium breath” (Blackadder and Manderson, 1975). Inhalation of Te may also lead to headache, drowsiness, nausea, dry mouth, and metal taste. Ingestion of Te may lead to gastrointestinal illness and can affect liver and central nervous system. The permissible exposure limit as established by OSHA for Te exposure in workplace is  $0.1 \text{ mg/m}^3$  over an 8-h workday, which is same as the REL given by NIOSH.

### **3.3.25 Biochemical toxicity of iodine (I)**

In 2015, 30,600 metric tons of Iodine was produced and two-thirds of the production came from Chile and the rest from Japan. It is used in several detectors (gamma counters), X-ray contrasting agents (medical imaging), LCD monitors, and special lamps (halogen lamps).

Iodine is an essential micronutrient for humans, required for synthesis of thyroid hormones and other physiological processes. Elemental iodine is toxic when taken orally with a lethal dose of 30 mg/kg and can cause irritation and damage to skin. A solution of iodine is often used as an antiseptic. Most common electrical and electronic equipment do not contain any iodine.

For adults who are not lactating or pregnant, the US Institute of Medicine, jointly with WHO, United Nations Children’s Fund (UNICEF), and the International Council for the Control of Iodine Deficiency Disorders (ICCIDD), recommend a daily iodine intake of  $150 \mu\text{g}$  and state a tolerable upper level

(the approximate threshold below which notable adverse effects are unlikely to occur in the healthy population) of 1100  $\mu\text{g}/\text{day}$  in adults (Leung and Braverman, 2014).

Farm animals fed with excessive dietary iodide displays symptoms of iodism such as hyperglycemia, hypercholesterolemia, and a neutrophilic-lymphopenic shift in blood leukocytes, besides lacrimation, coryza, conjunctivitis, coughing, hair loss, and exophthalmos. Excessive iodide interferes with body metabolism and affects immune functions (Hillman and Curtis, 1980).

The permissible exposure limit for iodine exposure at workplace is set at 1  $\text{mg}/\text{m}^3$  by OSHA for an 8-h workday, which is same as the REL set by NIOSH. However, 20 times this level, 20  $\text{mg}/\text{m}^3$  can prove to immediately detrimental to health and life.

### 3.3.26 Biochemical toxicity of tungsten (W)

Eighty-nine thousand metric tons of W was mined in 2015, and China accounted for more than 80% of the production. The metal is used for filament in various incandescent lamps (and also in vacuum tubes) but the major part of the world production goes into the tungsten carbide bits that are widely used in various engineering applications (gas and oil field drilling is a major consumer). W has toxic attributes similar to those of other heavy metals. These include hindering of seedling growth, reduction of root and shoot biomass, ultrastructural malformations of cell components, aberration of cell cycle, disruption of the cytoskeleton, and deregulation of gene expression related with programmed cell death (Adamakis et al., 2012). Because of the low volume of the metal in use, it does not pose a threat.

Experiments conducted on rats by implanting W pellets resulted in aggressive tumors indicating potential carcinogenic effect of W (Kalinich et al., 2005). Various studies have indicated ill effects of W exposure on reproduction, immune system, cardiovascular function, and neurobehavior (Witten et al., 2012).

### 3.3.27 Biochemical toxicity of platinum (Pt)

One hundred and eighty-nine tons of Pt was produced in 2015 and more than 70% of it came from South Africa. The metal is used in various chemical industries as a catalyst (also in automobiles with the same purpose) and to a small extent in electronic and in the manufacturing of precision glass. It is not an essential element and is also used in several cancer drugs (chemotherapy). The metal is rather inert chemically but an acute exposure to Pt may cause irritation of eyes, nose, and throat, whereas a chronic exposure can result in respiratory disorders and skin allergies. The permissible exposure limit as per OSHA standard is 2  $\mu\text{g}/\text{m}^3$  averaged over an 8-h workday, and the REL set by NIOSH for platinum exposure is 1  $\text{mg}/\text{m}^3$  over an 8-h workday.

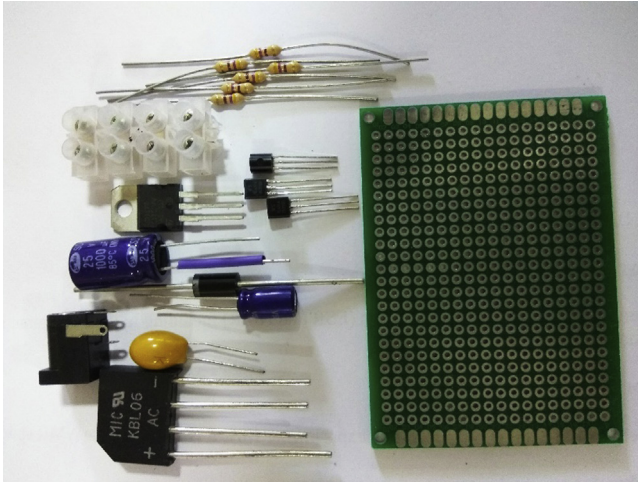
### 3.3.28 Biochemical toxicity of mercury (Hg)

The global annual production of Hg in 2015 was 3270 metric tons and 85% of this came from China. Hg is widely used in batteries, pesticides, fireworks, and in some

fairness (cosmetic) creams. Hg is a highly toxic element and is a cumulative poison. Small but significant amount of Hg is also present in all fluorescent lamps (that also makes the disposal of fluorescent lamps a hazardous process). There is a systematic attempt to replace major uses of Hg with less toxic products. Inorganic Hg salts can cause irritation in the gut and can damage kidneys. Organic Hg salts are capable of crossing the blood–brain barrier as they are fat-soluble and can cause neurological and behavioral disturbances (Langford and Ferner, 1999). Methylmercury is a potent neurological poison and can damage brain by affecting cerebellum and the visual cortex. Prenatal exposure to methylmercury can result in retarded development and cognitive impairment in children (Grandjean et al., 1997). Metallic Hg can evaporate at room temperature and thus is considered harmful. Also, it can be biotransformed to organic Hg in lakes and other water bodies, thus entering the food chain eventually reaching human. One such infamous incident was Hg poisoning which affected thousands of people in Minamata Bay in Japan and the disease was termed as Minamata disease. Dangerous amounts of Hg were found in fishes caught near Bombay (now Mumbai) that came from caustic soda manufacturing plants (using Castner–Kellner process; now being phased out). Major symptoms include numbness in limbs, impaired peripheral vision, hearing and speech, and muscle weakness. Severe toxicity may lead to insanity, paralysis, coma, and even death.

### 3.4 Plastics used in electronics and electrical items

Plastics are widely used in electrical and electronics devices. In electrical cables, plastics are used as insulators and as physical protection from the environment. Mechanical strength is often provided by a covering (cladding) of steel wires or tapes just below the outermost plastic sheath. Electronic items contain plastics as (1) protection to the component device and wires; (2) enclosure material (item can be enclosed in either plastic or metal); and in much smaller amounts as (3) special purpose adhesives. Polyvinylchloride (PVC) is one of the most common plastics that finds numerous applications (drain pipes to insulation for electrical wires). In 2016 the global production of the PVC was 62 million metric tons. The global production of electrical and electronic waste in 2012 was 42 million metric tons (of which 9.4 million metric tons were contributed by the United States and 7.3 million metric tons were contributed by China) (Vouvoudi et al., 2017). Although environment unfriendly, PVC is popular because the characteristics of the final product can be relatively easily manipulated by using special additives (often plasticizers) and it costs low. Most plastics are inflammable and for use in electronic and electrical items, some form of flame retardants is often used. Unfortunately, these compounds (brominated organic compounds that slow down, but do not completely prevent fire) are also toxic to the environment (because of the presence of bromine). Current trend is to reduce the use of PVC in both electrical and electronic items. Fig. 3.3 shows extensive use of plastic random assortment of electronic components.



**Figure 3.3** A random assortment of electronic components showing the extensive use of plastics.

Almost all domestic electric wires are insulated with PVC and at the end of their service life the cables are burnt to remove the plastic and recover the Cu (that can be recycled). However, PVC produces highly toxic fumes (unless burnt under controlled conditions in an incinerator) which causes air pollution. Phthalate esters are often used as plasticizers for PVC, but they too are environment unfriendly. Pyrolysis of the plastics present in the waste can produce a liquid fuel fraction but this has not been tried on a large scale (Vouvoudi et al., 2017). Polyethylene and cross-linked polyethylene are slowly replacing PVC for electric cable insulation. Polycarbonate plastics are popular for enclosures but recent concerns about the effects of bisphenol-A (substance of very high concern) have restricted their use.

Plastics are known for their long degradation process and therefore when disposed in landfill pose environmental risk. Brominated flame retardants (BFRs), PVC, and polychlorinated biphenyls (PCBs) are particularly toxic.

PCBs are used in capacitor and transformers. They affect systems including immune, endocrine, and nervous systems. IARC classified PCBs as a definite carcinogen in human in 2013 (Lauby-Secretan et al., 2013). Exposure to extremely high level of PCBs may lead to skin conditions as rashes, dermal and ocular lesions, and irregular menstrual cycles and lowered immune response (Aoki, 2001). Further, in children, it is reported to cause poor cognitive development. Pregnant women exposed to PCBs may give birth to children with compromised immune function and motor control problems (Jacobson and Jacobson, 1996). In animals, even a short exposure to PCBs can cause liver damage and can be fatal. Long-term exposure to small amounts of PCBs can cause ill effects to skin, liver, stomach, and immune system. It can also lead to hearing loss (Goldey et al., 1995).

PVC contains components as vinyl chloride monomer, which is a noted carcinogen in humans. Further, the presence of plasticizers is a prime concern; the most

commonly used plasticizer is phthalate which is a known carcinogen in rodents and is reported as a potential endocrine disruptor in humans (Kajta and Wójtowicz, 2013). Dioxins, released when PVC is incinerated, are toxic in nature and can cause nervous system disorder, birth defects, and even cancer (Matés et al., 2010). It is also found to cause reproductive, immune, and developmental system dysfunction (Thornton, 2002).

BFRs are ubiquitously used in various industry chemicals. Different BFRs have varying effect on humans and animals. Brominated diphenyl ethers (BDEs) are the most widely used category. It has been reported that PentaBDEs cause adverse effects even in lower doses, followed by OctaBDEs and DecaBDEs, which are harmful in comparatively higher doses only. They are reported to affect neurobehavioral development and thyroid, kidney and liver morphology (Darnierud, 2003). Several BFRs are linked to memory and learning problems, retarded physical and mental growth, lower IQ, and reduced fertility. These components tend to persist in environment and bioaccumulate. They have been detected in the tissue of sperm whales, which mostly inhabit in deep oceans, suggesting the long-distance transport and bioaccumulation (Boon et al., 2002).

A modern electronic consumer device may contain most of the possible elements mentioned above but they are in a sealed environment and do not appear to pose any direct hazard to the user. However, when disposed improperly, they (e.g., mercury from fluorescent lamps or lead present in solders) can seep into the environment and can pose a threat for many years to come (because the elements change their chemical form, but the toxic effects persist). Most plastics, by their commercial design, are essentially resistant to degradation and pose a direct threat to the environment (rather than humans) and modern economics makes recycling of plastics unattractive.

### 3.5 Current disposal methods

Major biochemical hazards are mediated by inappropriate disposal of electrical and electronic goods, where the individual components, especially the toxic elements (mentioned in the previous sections) which make its way in living systems. Once these goods are out-of-use and are discarded, the process of their disassembly starts. Post disassembly the individual components are either recycled, incinerated, or are deposited in a landfill. However, the choice of final disposal depends on the nature and characteristic of individual elements and should be taken into consideration before proceeding with disposal. It is generally a combination of these methods, where recycling marks the first step followed by incineration or landfilling or both.

It has been suggested that urban E-wastes can be mined to extract several rare and precious metals (Li, Au, Ag, Pd, In) since they have a much higher concentration compared to the natural mines (Wang et al., 2017). Considerable efficiency enhancement can be expected if some preliminary segregation can be done (e.g., Li can be used for batteries; Cu, Ag, Au, and Pd can be used in making printed circuit boards and In can be used for LCD panels). Both Pd and Pt can be recovered with high yield from catalytic converters of automobiles.

Recycling is supposed to be the most intensive step as it requires manual disassembly followed by several steps depending upon the item to be recycled, such as melting solder, shredding, grinding, and metal segregation. Recycling is opted to recover valuable components which can be repurposed and used further. During recycling may also release hazardous substances causing toxicity in living systems. For example, heating plastics (e.g., PVC) which contain bromine or chlorine leads to formation of dioxins and furans, which are released into the air; however, measures are being taken to reduce these emissions using proper handling techniques. The remaining components after recycling are either incinerated and landfilled or landfilled directly. Incineration is advantageous in some cases, whereas in others it might lead to further toxic and hazardous end products in the form of fly ash, slag, or wastewater being released into air, water, or land. Landfilling may sound to be a safe option for waste management, but the problem arises when the filled waste leaches or evaporates from the landfill.

### 3.6 Current recycling practices

Recycling can be undertaken at several places: (1) at the point of production, (2) at the assembly point, and (3) at the consumer level after the end of life of the item. At the factory where the material is produced, recycling makes the most economic sense. A part that could not be used becomes a waste and can be safely returned to the previous (or still earlier) stage where the recycled material will act as an input. This is a routine practice because it costs the least and reduces waste. This sometimes is not even considered as a recycling step.

Recycling at the assembly point is also easy to implement because of the volume involved. An automobile factory, for example, produces lots of steel scrap that can be sold back to the factory at a discount. An electronic assembly line can (and does) segregate all faulty circuit boards that are sold to a scrap dealer at a price. The scrap dealer has an idea of the rough composition of the lot and passes on the material to the factory that can make the most use of the material (e.g., a lot containing mostly printed circuit boards can be sent to a copper recovery agent who will also recover smaller amounts of Ag, Au, and Pd from the same boards). However, for economic reasons, the assembly line must reduce waste production and maximize efficiency. Hence the production of scrap at this stage is rather small (<1%).

The picture changes completely at the last step when the final user, at the end of life of the item, wishes to discard the item. The final product is distributed over many people and over a large geographical area. Recycling at this step is most important but is also difficult. Therefore a large amount of the material ends up as E-waste in a potential landfill.

Because of economic reasons, many countries decide to export their E-waste to other countries for final disassembly and disposal. Therefore E-waste disposal has become a major concern particularly in developing nations. E-wastes from



developed countries are being shipped to developing countries, such as India and Bangladesh, for recycling due to low-cost labor and weak environmental regulations (Agoramoorthy and Chakraborty, 2012).

For example, it has been reported that in 2016, over 2 million metric tons of E-waste was produced in India. It does not include the E-waste that India received in the same period (import of E-waste is officially banned in India). Because of lack of suitable infrastructure, only about 1%–2% of the E-waste was effectively recycled. One of the main reasons for the low efficiency of recycling is the lack of economic incentives. Economics dictate that wealthier countries that do have a decent E-waste collection system in place prefer to export them to third countries where the laws and regulations are rather lax or nonexistent (or not enforced). The E-waste in poorer countries is manually processed by women and children (two rather vulnerable groups) without proper safety safeguards.

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