Chapter 6

A Review of Technology of Metal Recovery from Electronic Waste

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Additional information is available at the end of the chapter

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Abstract

Electronic waste, or e-waste, is an emerging problem with developed nations as with developing nations. In the absence of proper collection and disposal systems, awareness, and proper regulations, the problem is rather more acute in developing nations. These wastes are environmentally hazardous on one hand and valuable on the other. They contain substantial amount of metal value, including precious metals. Personal computers are the biggest contributors to e-waste, followed closely by televisions and mobile phones. The growth in their consumption pattern indicates a manifold increase in the volume of e-waste and calls for immediate attention to the management of e-waste in general and their recycling and reuse in particular.

Their recovery, recycle, and reuse have become mandatory. Research and development work on their recycling has led to several technological options. However, a close investigation of the options reveals that there is no universally acceptable model for management of e-waste and they are still evolving. The technology for recycling depends on the economic status of the region along with several other factors. R&D efforts towards the management of e-waste and its recycling is seriously lacking in India.

There are three main constituents of e-waste, namely, glass, plastics, and metals. The glass may be re-melted for production of glass or for recovery of lead. The thermosetting plastics are difficult to recycle. The other types of plastics can be recycled for use as fuels or production of chemicals. The metals may be separated from the plastics and processed for recovery of individual metals. It may be said that physical separation techniques followed by metallurgical treatment is the best proposition for the recovery of metals. Detailed technology development needs to be taken up for the recycling of e-waste that may serve the interest of the region best.

Keywords: Electronic waste, collection and disposal, recycling practices, metal recovery

1. Introduction

Safe and sustainable disposal of End-of-Life (EOL) electronic waste has been considered to be a major sphere of concern both by the government and public as well, due to its perilous impact on human life and environment, arising from its hazardous and highly toxic constituents. Disposal of such heterogeneous mix of organic materials, metals, etc., entails a scientific approach and special treatment to prevent exposing the inhabitants to the consequential damage implications arising from leakage and dissipation of the same for effectively mitigating the emerging risk phenomena escalating with the passage of time [1–6]. The threat perception arising over the last decade from accelerated accumulation of e-waste on account of the emerging consumption patterns across all sections of the society, influenced by the associated advantages ranging from affordability to comfort in day-to-day utility with respect to computers, cell phones, and other personal electronic equipment has been found to be phenomenal. It is now imperative for the society at large to evolve safe and scientific methodologies, both as a deterrent to the impending damage potential to the environment and also for recovering economically the embedded valuable and rare metals in contributing to immense value addition to the waste, which otherwise leads to large scale environmental and ground water pollution. Recycling, recovering, and reusing of obsolete electronics in new product cycles have now been globally recognized as a formidable challenge, taking into account the inherent value addition potential of metals such as gold, silver, copper, palladium, including rare metals, etc., which has immensely contributed to the concept of recycling to be a very lucrative business opportunity in both developed as well as developing countries. Also, the sheer volume of such waste generated on account of the present-day usage pattern poses a formidable problem in terms of storage handling and disposal space, which as a natural corollary, happens to be a major trigger across the globe for processing these wastes aimed at effectively extracting the metal values and remove the non-metallic constituents.

According to the United Nations (UN), the initiative to estimate e-waste production, the world produced approximately 50 million tons of e-waste in 2012, on an average of 15 lbs. per person across the globe. In 2012, the UN also stated that, the United Kingdom (UK) produced, 1.3 million tons of e-waste. China generated 11.1 million tons of e-waste that was followed by the United States (US) that accounted for 10 million tons in 2012 [7]. In Western Europe, 6 million tons of electric and electronic wastes were generated in 1998. The amount of this waste is expected to increase by at least 3–5% per annum [1]. This study also indicated that in the US, over 315 million computers would be at EOL by the year 2004. The same scenario applies to mobile phones and other hand-held electronic items used in the present society. In 2007, over 130 million mobile phones were discarded alone in the US and by 2010 in Japan, 610 million mobile phones will be disposed off. Every year, a European Union citizen leaves behind nearly 20 kg of e-waste [2]. The problem of e-waste is global, for example, in China about 20 million consumer electronic and electric equipment (EEEs) and 70 million mobile phones reach EOL each year [8] and in India computer ownership per capita grew 604% during the period 1993–2000 far exceeding the world average of 181% [9]. About 4000 tons per hour of e-waste is generated worldwide [10]. The printed circuit board (PCB) is a major constituent of these obsolete and discarded electronic scraps. The typical composition of PCB is non-metals (plastics, epoxy resins, glass) >70%, copper ~16%, solder ~4%, iron, ferrite ~3%, nickel ~2%, silver 0.05%, gold 0.03%, palladium 0.01%, others (bismuth, antimony, tantalum, etc.) <0.01% [11].

Veit et al. [12] reported a combination of magnetic and electrostatic separation for removing metallics from non-metallics. The authors reported that it is possible to obtain a fraction concentrated in metals containing more than 50% of copper, 24% of tin, and 8% of lead. Zhang and Forssberg [13] have done extensive work on liberation and classification of electronic scrap. In this work, liberation and its impact on the separation of computer scrap and PCB scrap has been studied. In Taiwan, research is being carried out on the processing of scrap computers with a view to recycling. It is reported that a recycling plant can recover useful materials from the main machines and monitors of scrap computers to the extent of 94.75 wt % and 45.99 wt%, respectively [14]. This study also deals with the processing of cathode ray tubes (CRTs) and PCBs separately. Zhang and Forssberg [15] studied electrodynamic separation and reported that copper products with the grade ranging from 93% to 99% and recovery from 95% to 99% can be achieved by this technique.

An excellent review by Williams [16] presented the current scope of technology, recycling process design, and controls. The author also indicated the direction of future research emphasizing the needs of automated processes, controls, and optimum data acquisition. Kang and Schoenung [17] have also presented a review of technology options for recovery of materials from e-waste. Various recycling technologies for glass, plastics, and metals that are present in electronic scrap are discussed. The authors emphasized the need for a stable supply of scrap, a cost-effective technology for recycling, and a stable demand of recycled materials for the success of the electronic scrap recycling industry.

In spite of having several technological options, it appears that a quest for a cost-effective technology for processing electronic scrap is still on. Yokoyama and Iji [18] have invented a dry separation method for recovering valuable metals from PCBs. Their method is based on two-step grinding of the boards, followed by air current centrifugal classification for gravity separation and electrostatic separation. Menad et al. [19] suggested that plastics contained in the electronic scrap may be used as combustible in some metallurgical processes. However, the authors cautioned that during combustion, halogenated flame retardants present in them would produce dibenzo-dioxins and dibenzo-furans, which are hazardous. Zhang et al. [20] have proposed an eddy-current method for recovering aluminum metals from PCB and personal computer scrap. It is reported that materials on the High-force eddy-current separator, an aluminum concentrate out of personal computer scrap can be obtained with a purity of 85%, while maintaining a recovery in excess of 90%, with the feed rate being up to 0.3 kg/min. Sinha-Khetriwal et al. [9] compared the recycling of e-waste in Switzerland as one of the few countries with long-term experience in managing e-waste in India, which handles huge amounts of imported e-waste, but is continually experiencing problems. Market players are taking measures to recycle e-waste in order to reduce the pollution and environmental hazards caused by it. In June 2014, Dell, a leading computer manufacturer, launched its first computer that is made of plastics obtained from recycled electronics. The company has started selling its first computer "the OptiPlex 3030", which is made up of old electronics using the closed loop recycling process. Recently, Dell has also started using recycled plastics in its other desktops and monitors. Millions of refrigerators, TV sets, and cell phones are replaced with newer versions due to the users' growing inclination towards technologically advanced gadgets [7].

Developed countries such as the US, Europe, and Japan have adopted fully automated, high-cost technology for e-waste recycling [21]. E-waste is crushed, shredded in total, followed by the separation of metals and non-metals by adopting unit operations/metallurgical principles. The disposal and recycling of e-waste, particularly computer and related wastes, in India, has become a serious problem since the methods of disposal are very rudimentary and pose grave environmental and health hazards. The situation is aggravated as current e-waste management and disposal methods suffer from a number of drawbacks such as inadequate legislations, lack of funds, poor awareness, and reluctance on the part of the governments and the corporate organizations to address the critical issues. In view of the dwindling reserve of good quality metallic ore for production of metals, environmental pollution, and need for recycle, an indigenous technology for processing this waste is certainly necessary today. In India, e-waste management assumes greater significance not only due to the generation of its own e-waste but also because of the dumping of e-waste from developed countries. Solid waste management, which is already a mammoth task in India, has become more complicated by the invasion of e-waste. There is an urgent need for exploring different options of e-waste recycling in developing countries.

The present review article provides an overview of India's current e-waste scenario, environmental and health hazards, current disposal, collection, and recycling. It also provides a comprehensive view of the technologies available in the developed countries as well as the developing countries for the recycling of e-waste. The review research methodology as adopted by the researcher and proceeds encompasses reliability factor designed to deliver a balanced view from both macro and micro perspective of process feasibility and economics as well, based on authentic information about growth and forecasts.

2. E-waste and its composition

2.1. Definition of e-waste

Electronic waste or e-waste, according to the WEEE directive of the European Commission, is defined as waste material consisting of any broken or unwanted electronic appliance. Electronic waste includes computers, entertainment electronics, mobile phones, and other electronic items that have been discarded by their original users. Despite its common classification as a waste, disposed electronics is a category of considerable secondary resource due to its significant suitability for direct reuse (for example, many fully functional computers and components are discarded during upgrades), refurbishing, and material recycling of its constituent raw materials [22].

2.2. The key benefits for recycling EOL e-waste

E-waste is the most rapidly growing segment of the municipal waste stream and the Global E-waste Management Market is expected to reach $49.4 billion by 2020, with compounded annual growth rate (CAGR) of 23.5% (2014–2020), with maximum share of e-waste management market attributable to information technology (IT) and telecommunications, followed

by household appliances and consumer electronic goods. E-waste contains many valuable, recoverable materials such as aluminum, ferrous metals, copper, gold, and silver. In order to conserve natural resources and the energy needed to produce new electronic equipment from virgin resources, electronic equipment should be refurbished, reused, and recycled whenever possible. E-waste also contains toxic and hazardous waste materials including mercury, lead, cadmium, chromium, antimony, and many other chemicals. Recycling will prevent them from posing an environmental hazard.

2.3. Health and environmental impact of e-waste

EOL of electrical and electronic equipments comprise numerous components, many of which are inherently hazardous and highly toxic in nature, which if not arrested through scientifically sustainable recycling and disposal, can lead to a disastrous impact on life, environment, and climate as well. Certain examples of sources of e-waste and their related adverse health impacts are listed in Table 1 [23]. However, if handled in a controlled environment and disposed-off adopting safe and sustainable methodology, these e-wastes provide immense value addition and new product cycle, driving great economic prospect, without posing risks to life, environment, and climate. However, haphazard recycling and disposal of e-waste by the unorganized sector without access to adequate technology and resources, guided by profit-only motive can have damaging consequences to inhabitants and the environment, including but not limited to the workforce engaged in this trade, groundwater pollution, etc., especially on account of highly toxic release into the soil, air, and ground water [23].

E-waste sources	Constitutents	Health effects
Solder in PCBs, glass panels, and gaskets in computer monitors	Lead	Causes damage to the nervous system, circulatory system, and kidney. Also affects brain developments in children.
Chip resistors and semiconductors	Cadmium	Causes neural damage.
Relays and switches, PCBs	Mercury	Cause chronic damage to the brain and respiratory and skin disorders.
Corrosion protection of untreated galvanized steel plates, decorator, or hardener for steel housing	Hexavalent chromiun	Causes bronchitis and DNA damage.
Cabling and computer housing	Plastics including PVC	Affects the reproductive system and immune system and lead to hormonal disorder.
Plastic housing of electronic equipments and circuit boards	Brominated flame retardants	Disrupts endocrine system functions.
Front panel of CRTs	Barium, phosphor, and heavy metals	Causes muscle weakness and damage to heart, liver, and spleen.
Motherboard	Beryllium	Carcinogenic in nature causing skin diseases

Table 1. E-waste sources and their health effects.

Landfilling, being one of the widely prevalent methods of e-waste disposal, is as such prone to hazardous implications attributable to leachate that often contains heavy metals, and this equally applies to the state-of-the-art landfills methodologies that are adopted or sealed for the long-term. The older landfill sites and uncontrolled dumps factually pose a much greater danger of releasing hazardous emissions, since mercury, cadmium, and lead comprise the most toxic elements of the leachates (Table 1). Mercury, for example, will leach when certain electronic devices such as circuit breakers, etc., are subjected to disposal and recycling; lead has been found to leach from broken lead-containing glasses, such as the cone glass of CRTs from televisions and monitors; when brominated flame-retarded plastics or plastics containing cadmium are landfilled, both PBDE (polybrominated diphenyl ethers) and cadmium may leach out into the soil and groundwater. In addition, landfills are also prone to uncontrolled fire, release source for toxic fumes [23].

The toxicity is due in part to lead, mercury, cadmium, beryllium, Brominated Flame Retardants (BFRs), PVC, and phosphorus compounds and a number of other substances. A typical computer monitor may contain more than 6% lead by weight, much of which is in the lead glass of the CRT. Up to thirty-eight separate chemical elements are incorporated into e-waste items. Though some of the materials are used in small quantities in each computer, the net volumes being recycled are significant and have a huge impact on both environment and human health. The unsustainability of discarding electronic items is another reason for the need to recycle—or perhaps more practically, reuse e-waste. Quantification of some of the toxic elements present in an average computer, weighing approximately 31.5 kg [24] shown in Table 2.

Element	Quantity
Plastics	7.24 kg
Lead	1.98 kg
Mercury	0.693 g
Arsenic	0.4095 g
Cadmium	2.961 g
Chromium	1.98 g
Barium	9.92 g
Beryllium	4.94 g

Table 2. Toxic elements present in an average computer.

Given the diverse range of materials found in WEEE, it is difficult to give a generalized material composition for the entire waste stream. However, most studies examine five categories of materials: ferrous metals, non-ferrous metals, glass, plastics, and others. Figure 1 shows the material fractions in e-waste [2]. Metals are the major common materials found in e-waste representing about 60%. Plastics are the second largest component by weight representing about 15%. Figures 2—4 shows the material composition of a personal computer [25, 26], followed by television sets [27] and mobile phones [28].

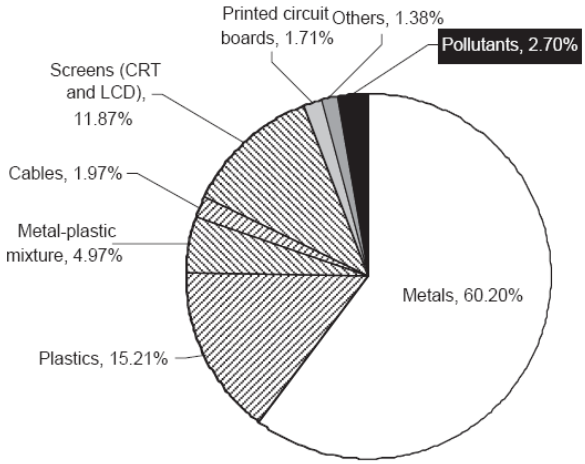

Figure 1. Material fractions in e-waste [2].

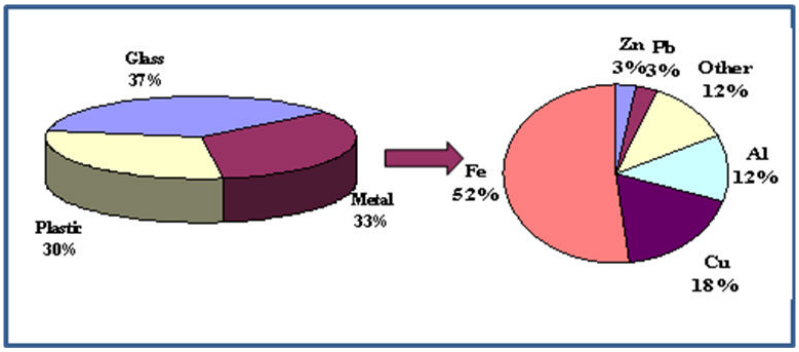

Figure 2. Material composition of a typical computer.

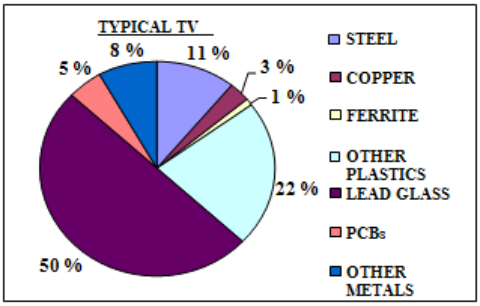

Figure 3. Material composition of a typical TV.

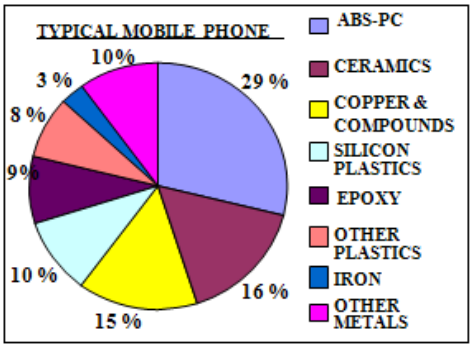

Figure 4. Material composition of a typical mobile phone.

3. E-waste scenario

3.1. Global scenario

Accelerated generation of e-waste with passage of time happens to be the natural outcome of incremental penetration of IT in diverse spheres of day-to-day activities, adding up to the municipal solid waste stream. E-waste equals 1% of solid waste on average in developed countries and ranges from 0.01% to 1% in developing countries [29], and the same is expected to inch up considerably in the near future. Some of the developed countries such as the US, UK, Germany, Japan, and New Zealand have already developed advanced processing techniques for recycling of the e-waste and patented them, as well. The Union Miniere Company in Belgium [30] and Boliden Mineral in Sweden [31] have, since quite some time, been operating recycling plants to process e-waste, while in China [32–36], Taiwan [14, 37], and South Korea [38] proactive measures are being pursued to recycle metal from e-waste, but in India, no concrete or notable steps have been initiated so far in the large scale or in structured format. Das et al. [39] developed a flowsheet using a combination of wet and dry processes to produce a rich concentrate with significantly high recoveries of metals from ground PCB powder.

Every year, 20 to 50 million tons of electrical and electronic equipment wastes are discarded worldwide and Asian countries discard an estimated of 12 million tons [40]. The share of the developing economies of China, India, etc., with respect to consumption of computers in particular, is likely to surge ahead, surpassing 178 million in case of China and 80 million in case of India, out of the estimated 716 million new computer users' global total [41]. E-waste generated in developed countries such as the US, etc., is often exported for recycling in developing countries where labor is relatively cheap, apart from the prospect of ending up as landfill, and as a result, the pollution menace is accelerating at very fast pace, especially in countries such as China, India, and Pakistan, posing severe health and environmental hazard.

Rampant approach of open-air burning of plastic wastes, toxic solders, river dumping of acids, and widespread dumping and landfill in general [25]. A report from the International Association of Electronics Recyclers states that around 3 billion units are expected to be scrapped in the remaining years for the decade to end in the US alone, which works out to an average of about 400 million units a year, that includes 200 million televisions and 1 billion units of computer equipment. According to Basel Action Network (BAN), about 75% of old electronics are in the offing to be scrapped in near future, which at present have been kept in abeyance by the consumers, with the expectation being nurtured by them that they still have some usage value left and at the same time remaining uncertain about its disposal methodology to be adopted [42]. Most of the e-waste produced by developed countries is dumped in developing and under-developed countries.

3.2. Indian scenario

As there exists no dedicated or systematic collection provision for e-waste in India, no clear data is available on the quantity actually generated and disposed off each year and the extent of resultant environmental risk. The MAIT-GTZ study [43] reported that a total of 330,000 metric tons of e-waste (computers, televisions, and mobile handsets only) was generated in 2007. An additional 50,000 tons were unscrupulously imported into the country, mostly mislabeled as charitable donations or scrap, and not specified as electronic scrap, generating a annual e-waste of about 380,000 metric tons. Of this, only 19,000 tons were recycled, which was factually complemented by the demand for refurbishing and reuse of electronic products in the country and poor recycling infrastructure set-up in the unrecognized sector with profiteering motive. Generation of e-waste in India is estimated to far exceed 470,000 metric tons as on 2011, out of which Mumbai generates around 11,000 tons of e-waste, Delhi 9000 tons, Bengaluru 8000 tons and Chennai 5000–6000 tons each year. Maharastra State (including Mumbai city) alone produces 20,270 tons of e-waste annually [44]. The Electronic Industry Association (ELCINA) in India has predicted that e-waste will increase by 11 times as on 2012, since the average lifespan of a personal computer is reduced to around 2 years. The per capita waste production in developing countries such as India and China, is still relatively small, estimated less than 1 kg per capita per year. In India electronic goods such as computers, washing machines, televisions, and refrigerators will drive the future growth of the electronics hardware industry. The e-waste generated from these four items during 2004–2005 was found to be 1,46,180.00 tons and it was expected to exceed to about 16, 00,000 tons by 2010 [45].

In India, the problem of e-waste generation and disposal is steadily attaining an alarming dimension with passage of time. It has been reported that 900–1000 computers are dismantled every day in New Delhi alone. In 2005, about 1000 tons of plastics, the same equivalent of iron, 300 tons of lead, 0.23 tons of mercury, 43 tons of nickel, and 350 tons of copper were expected to be generated as e-waste in Bengaluru alone [46]. These figures are set to increase by ten-fold by 2020. In India, Maharashtra, Tamilnadu, and Andhra Pradesh head the list of e-waste generating states. Cities such as Delhi, Chennai, Kolkata, and Bengaluru contribute significantly to the e-waste generation as well. A study done by Toxics Link in 2007 [47] estimated that Mumbai alone produces 19,000 tons of WEEE annually. Another study had done jointly

by Toxics Link and the Centre for Quality Management Systems, Jadavpur University, Kolkata estimates around 9000 tons of WEEE generation in the city of Kolkata [48]. The future projection of e-waste in India as per the Department of Information Technology is shown in Figure 5.

Figure 5. State-wise e-waste generation in India.

The results of a field survey conducted in Chennai, a metropolitan city of India, to assess the average usage and life of the personal computers (PCs), televisions (TVs), and mobile phones demonstrated that the average household usage of the PC ranges from 0.39 to 1.70 depending on the income class [49]. Although the per-capita waste production in India is still relatively small, the total absolute volume of wastes generated is gigantic, and it continues to grow at an alarmingly fast rate. The growth rate of mobile phones (80%) is very high compared to that of PCs (20%) and TVs (18%). The public awareness on e-wastes and the willingness of the public to pay for e-waste management, as assessed during the study, based on an organized questionnaire revealed that about 50% of the public are aware of environmental and health impacts of EOL electronic items. The willingness of the public to pay for e-waste management ranges from 3.57% to 5.92% of the product cost for PCs, 3.94% to 5.95% for TV and 3.4% to 5% for the mobile phones [50].

4. E-waste sources and growth pattern

4.1. E-waste sources

The main sources of e-waste in India comprises the government, public, and private (industrial) sector discards, which account for almost 70% of the total e-waste generation. The growth in the government sector alone has been a staggering 126% as of 2006 [26]. Important government departments such as Railways, Defense, and Healthcare have been estimated to generate large volumes of e-waste. In India, most organizations upgrade their hardware infrastructure at an interval of 3–5 years, and at times much earlier influenced by the benefit in rate of

allowable depreciation. Electronics goods are high price items and hence are not dumped in streets or garbage yards. These are stored in houses or warehouses for a long period of time and subsequently either passed on to or sold to scrap dealers for monetizing, however, this practice is set to change with time. The contribution of individual households is relatively small at about 15 % while the balance is contributed by the commercial or business segment. Though individual households are not large contributors to computer waste generation, large-scale consumption of consumer durables such as televisions, refrigerators, air conditioners, etc., are certainly attributable to this segment. The trend of extended usage is also changing with rapid advancements in technology and further complemented by lower product costs, which is leading to scaled-up generation of domestic e-waste.

Another major source of e-waste is unscrupulous import, which is adding to the volume of waste being generated within the country, however, accurate data on such imports are not available, owing largely to the nature of the trade. Developing countries, including India, have been the destination ports for various types of hazardous waste from the developed world and e-waste is no exception. Industrialized nations are scrounging for space for landfills to dispose of huge amounts of e-waste being generated by them and with strict environmental regimes being put to practice, especially in European countries, thereby, adding to the cost of disposal [51]. As per available data, the cost of recycling a single computer in the US is US$20 while the same could be recycled in India for only US$2, a gross saving of US$18 if the computer is exported to India [51]. Most developed countries stand to benefit economically by dumping e-wastes in developing countries.

The lack of stringent environmental regulations, weak enforcement mechanism, cheap raw materials and labor, and ill-informed population in combination with the unorganized nature of the trade contributes significantly to the growing imports of e-waste in India. Even though the import of e-waste is banned in India, there are many reports of such waste landing in Indian ports under different nomenclature, such as mixed metal scrap or as goods meant for charity [51]. However, estimates suggest that unscrupulous imports of e-waste are equal to or even more than that being generated in the country.

4.2. Growth of e-waste

Electronic and electrical goods are largely classified under three major heads: 'white goods', comprise household appliances such as air conditioners, dishwashers, refrigerators, and washing machines; "brown goods" such as televisions, camcorders, cameras; and "gray goods" such as computers, printers, fax machines, scanners, etc. These gray goods are comparatively more complex to recycle due to their multi-layered configuration and higher toxic composition. The last decade has also witnessed major growth in the gray goods market and India is expected to achieve a PC penetration rate of 65 per one thousand by the year 2008 [52].

The PC sales figure in India has been very impressive, showing a huge growth from a mere 14,05,290 in 1999–2000 to 46,14,724 in 2005–2006 and is conservatively projected to touch 56,00,000 by 2006–2007. The expected annual average growth rate in the PC is likely to be 21%, while consumption of PC in the top four cities (Delhi, Mumbai, Kolkata, Chennai) grew by 25% as on 2006 [48]. For the laptop segment, the growth is more impressive; the sales figure

has jumped from 50,954 in 2002–2003 to 4,31,834 in 2005–2006 having registered an astonishing growth rate of 143% in 2005–2006 [48,52]. The overall PC sales in 2012–2013 considerably slowed down and the sales figure are well below the expectations. The overall sales figures touched 11.31 million in 2012–2013, registering a growth of 5% over the last fiscal. Desktop PCs continued to dominate the sales proceedings contributing around 60% of the sales although it is somewhat lesser than last year's contribution of 63%. Notebook sales posted a muted growth rate of 10% in 2012–2013 compared to the 22% rate in the previous year. Tablet PCs witnessed a massive growth rate of 424%. The sales for 2012–2013 stood at 1.9 million units as against 0.36 million units in 2011–2012 [53]. Sixty-five cities in India generate more than 60% of the total e-waste generated in India. Ten states generate 70% of the total e-waste in India [54]. Maharashtra ranks first followed by Tamil Nadu, Andhra Pradesh, Uttar Pradesh, West Bengal, Delhi, Karnataka, Gujarat, Madhya Pradesh, and Punjab in the list of e-waste generating states in India (Figure 6). According to forecast, based on a logistic model and material flow analysis [55], the volume of obsolete PCs generated in developing regions will exceed that of developed regions by 2016–2018. By 2030, there would be two obsolete PCs in the developing world for every obsolete PC in the developed world. Similar forecasts have been arrived independently [56]. The advent of LCD, plasma, and larger screens has changed the way India views television and this has translated into phenomenal growth in sales, resulting in a considerable surge in rate of disposal as well.

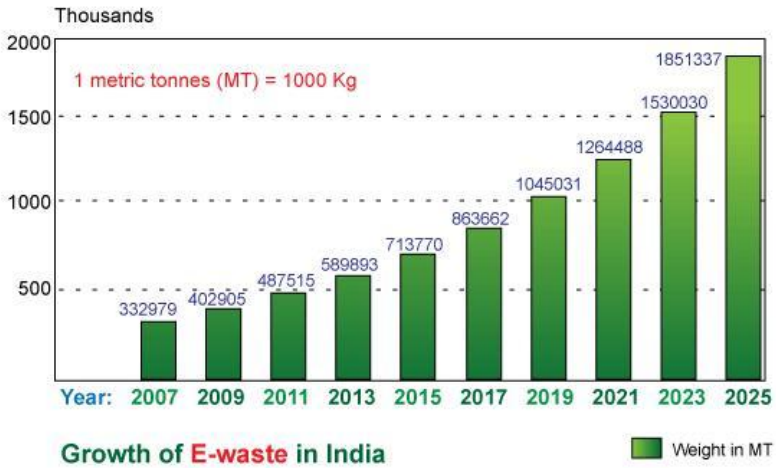

Figure 6. E-waste generation in India: Past and forecasts for the future.

There are over 75 million mobile users and the number has increased to 200 million as of 2008 [57]. An estimated 30,000 computers become obsolete every year from the IT industry in Bengaluru alone [58]. India has about 15 million computers and the base is expected to grow to 75 million computers by 2010 since the life cycle of a PC has come down to 3–4 years from 7 to 8 years a few years back, and the segment is suffering from an extremely high obsolescence

rate of 30% per year [58]. The rapid growth in industrialization is immensely contributing to the generation of huge quantities of waste. Some of the recent studies on e-waste generation clearly reflect that this trend is likely to grow at a phenomenal rate, while penetrating to smaller towns and cities.

Another important contributing factor to incremental waste generation is the high obsolescence rate of these products and the inability of technology to support upgradation from the perspective of economic viability. This consumption pattern and programmed obsolescence is a part of business management strategy in planning in-built product design with limited life that promotes a high-waste economy targeted at people with higher disposable income. Every two years, a new computer model is introduced in the market, rendering the previous one obsolete. The Indian mindset has so far been able to prolong the usage of such products by devising innovative solutions; however, this approach is undergoing gradual change after being bitten by the new bug of consumerism.

5. E-waste disposal methods and recycling practices

5.1. E-waste disposal methods

Computer scrap in India is handled through various approaches in management alternatives such as product reuse, conventional disposal in landfills, incineration, and recycling. The recycling of computer waste requires efficient and advanced processing technology, which apart from being capital intensive, entails high-end operational skills and training of the processing personnel. However, the disposal and recycling of EOL computers in the country has become a menacing problem compounded on account of rudimentary methodology for disposal and recycling by entrepreneurs in the unorganized sector drawn more with profiteering motive, despite not having adequate access to sustainable technology, thereby posing grave environmental and health hazards. Apart from having to handle its own burden arising from the accelerated accumulation of EOL-EEEs, India now faces the herculean task in managing the waste being especially dumped by developed countries, leading to rapid escalation of the risk phenomena associated to solid waste management, particularly computer waste. Taking advantage of the relative slackness on environmental standards and working conditions in developing countries, vis-à-vis stringent environmental norms followed in the developed countries, e-waste is being sent or dumped for processing in India and China—in most cases, illegally. The random open-air disposal of e-waste, including incineration, is factually contributing to the rapid escalation in pollution menace, affecting both life and environment. Currently, the likely modes of disposing e-waste discussed in the following sections.

5.1.1. Product reuse

Refurbishing used computers and other electronic goods for reuse after minor modifications, apart from the prevalent trend of passing on the same to relatives and friends, is a common societal practice. Apart from this, being lured by the retailers to monetise the old gadgets by

exchanging against new gadgets, in the form of additional discounts, are factually marketing gimmicks for accelerating sales volume. The actual benefits to the customer in the new for old exchange exercise, more often than not, are notional in reality, when viewed in perspective from commercial angle. There are instances when educational institutes or charitable institutions receive old computers for reuse. Such deemed unhealthy practice adopted for product reuse, despite their limited life span, which sooner or later ends up as waste, contributes significantly to the burgeoning burden of computer waste.

5.1.2. Conventional disposal in landfills

The product is dumped in landfill sites, where it may remain indefinitely. According to the Environmental Protection Agency (EPA), more than 3.2 million tons of e-waste ended up in US landfills in 1997 [59]. The extremely low biodegradable characteristics of plastic components in computers gets further compounded in dry conditions, which complements landfills and in strictly regulated landfill sites, degradation is even slower. The highly toxic constituents found in the different components of a computer contributes to metal leaching, leading to large-scale soil and groundwater pollution, and the situation worsens with passage of time for sites subjected to dumping for prolonged periods of time. When disposed off in landfills, the multi-layered configuration of computer waste becomes a conglomeration of plastic and steel casings, circuit boards, glass tubes, wires, and other assorted parts and materials. About 70% of heavy metals (including mercury and cadmium) found in landfills come from electronic discards [60]. In 2001 CRTs were banned from municipal landfills in California and Massachusetts because of their recognized hazardous nature, while no such regulatory measures are enforced in developing countries such as India, China, etc.

5.1.3. Incineration or open-air burning

After manual separation of components, motherboards are introduced to open pit burning for extracting the thin layer of copper foils laminated in the circuit board, which after charring, is distilled through a simple froth floating process. The ash is washed out and the copper, with some carbon impurity, goes to the next recycling stage. The defective IC chips and condensers, which do not have a resale value, are burned in small enclosures with chimneys for extracting the embedded metallic parts [26].

5.1.4. Recycling

Recycling practices for discarded personal computers are highly local and rudimentary, albeit, the metal value recovered from computer waste lessens considerably the disposal burden and consequent financial costs. Though a good fraction of computer waste is recycled in the process, the unscientific methodology adopted for material salvaging has an extremely high environment and health hazard impact attached to it as a natural corollary to the deployment of rudimentary recycling and recovery process and its damaging implications both on life and environment. Apart from the challenges explained, such method of recycling has its inherent limitations with respect to recovery of both metals and non-metals e.g., copper, gold, silver, aluminum, iron, tin, lead, and plastics are recovered to some extent while such processing

technique does not aid value addition in a true sense, keeping in mind the fact that many vital metallic components, such as germanium, barium, platinum, antimony, cobalt, nickel, etc. remain unrecovered.

6. Recycling practices of e-waste

Recycling of e-waste, especially EOL-EEEs, such as computers and mobile phones, provides lucrative business opportunity for extraction of valuable metals such as gold, silver, copper, lead, etc. Currently, e-waste recycling in India, especially processing, to a large extent, almost 95%, remains confined to the unorganized sector, which due to its inaccessibility to scientifically focused and sustainable processing technologies with added constraints of limitation in processing capacity, contributes significantly to pollution and environmental degradation. This trade has mostly grown on the fringes of metropolitan and larger cities surrounding the industry hub, however, with incremental growth in processing of e-waste, a shift to the periphery of smaller towns has also been observed of late. The phenomena of e-waste processing comprising dismantling and recycling for extracting valuable metals from PCBs, including CRT re-gunning, etc., adopting crude process methodology such as open-air burning or incineration, use of acid bath, etc., is primarily focused upon profiteering motive with minimal capital investment. This leads to escalating the grave damage implications for both life and environment, apart from endangering both the lives of workers engaged in the processing activities and the residents of the surrounding localities.

The recycling operations, as explained above, employs a large section of the underprivileged population, especially migrant unskilled laborers, including women and children, depending on this trade for their day-to-day livelihood. The role of the unorganized sector involved in the processing of such highly complex waste, exposing the life and environment to toxic pollution, has since long been a subject of debate in the scientific sphere and the society at large. Effectively, the real cause of concern for the escalating scenario emerging from such ill-focused trade undertaken by the unorganized sector, hinging on primitive process methodology, as adopted by them, and not on the trade or the stakeholders per se. However, it also needs to be appreciated that the unorganized trade activities undertaken in this connection contributes to the retrieval of a large percentage of the waste material and circulating back the same to a new product cycle, based on its innovative and economical techniques, albeit rudimentary, as developed by them, thereby, circumventing tons of e-waste being sent to landfills, while generating wealth from the huge waste. Open-air burning of plastics, PVC-coated wires, and PCBs are known to produce carcinogens such as dioxin and furan emissions [61]. The recovery of lead from circuit boards also emits dioxin and other chlorine compounds into the air. Broken picture tubes, contaminated with lead and barium, land up in glass manufacturing units. Thus, CRT glass, with a significant percentage of mercury and lead, re-enters the consumer's domain as a new recycled product [62], while most of the population unfortunately continue to remain ignorant about the grave health and environmental risks associated with rudimentary processing of e-waste. On the other hand, non-recyclable

components are either dumped as landfill or burned in the open, releasing toxins into the environment.

Recycling of EOL PCs is a very complex process on account of its multi-layered configuration comprising numerous materials and components aimed at recovering the valuable metals and other ingredients factually entails deployment of advanced processing technology and skilled technical personnel. This can effectively meet the pre-requisite safety norms for arresting the damage consequences, as explained, which as such is not generally accessible by recyclers in the unorganized sector, who are engaged in salvaging the wealth from waste, on account of multiple constraints ranging from finances, scalability factor, etc., including but not limited to ignorance as well. Technology limitations notwithstanding, each PC component is either refurbished for reuse or disassembled and recycled in India. However, liquid crystal displays (LCDs) are rapidly replacing cathode tubes, but the menacingly escalating implications, especially with respect to TV and PC waste, essentially needs to be encountered in the decade ahead; therefore, safety and solution to the impending environmental disaster lies in recycling of the same in industry scale by the organized sector [63, 64]. Computer monitors and TVs are disassembled to recover CRT, copper yoke plastic casing, and plates. The functional CRTs are sold for re-gunning as re-charged tubes, which has a potential sale value among local manufacturers. The defective CRTs are broken down to recover iron frames, which are sold to the scrap merchants. The copper recovered from deflection yoke coils and transformers mounted in the circuit boards are sold to copper smelters. The circuit tray contains a number of condensers of different sizes, which are disassembled to sell at secondary markets based on their functionality. Defective condensers are sold along with the motherboard for recovery of precious metal. The casing of monitors and TVs, including the insulator of copper wire and cable, comprises of either PVC (polyvinyl chloride) or a combination of both PVC and ABS (acrylonitrile-butadiene styrene), however, PVC is not recyclable due to the presence of high silicate percentage. ABS is recycled into high impact plastic, mostly for consumption by toy manufacturers. The recovery methods followed [26] by the units in the unorganized sector in India for various components are described in the Table 3. The recovery of the components from e-waste depends on their market value, while the residue and leftover such as ashes and plastic residues from charred IC chips, condensers, etc., are disposed off in landfills.

The recycling process broadly involves shredding, sorting, grading, compacting, bailing, or processing clean plastics and scrap metal. After segregating at source, physical separation, identification, and testing are carried out. Present recovery practices, however, broadly comprises glass, plastic, copper, aluminum, iron, etc., and do not cover precious metals. Recovery of precious elements, albeit being a very technologically challenging task, is vital from the economic perspective and presently, electronic waste in the form of populated PCB components is exported to various countries to accomplish the objective of recovering these elements, on account of technology limitations in India. The recovery aspects of certain valuable elements such as silver (Ag), gold (Au), palladium (Pd), tantalum (Ta), ruthenium (Ru), indium (In), gallium (Ga), beryllium (Be), etc., which are present in traces, have not been explored so far since the economy of scale and processing feasibility is factually determined by the recoverability aspect, taking into account the quantitative presence of the same (in

Items	Recovered Module /Component / Materials	Methods employed
Computer monitor, TV	• Cathode ray tube • Circuit board • Copper, steel • Glass • Plastic casing	• Dismantling manually using screwdrivers and pliers • Nonworking CRT broken with hammer
CPU/Hard disk of computer	• Metals (steel, aluminum) • Non-metals parts • Actuator (magnet) • Platter • Circuit board • Disk, floppy drive • SNPS (Power supply)	• Manual with help of screwdriver, hammer, and pliers
Populated PCB	• Capacitor & condenser • Gold • Copper • Lead, IC, CPU • Chipped board	• After preheating plate, removed with the help of pliers • Acid treatment/bath • Heating, incineration • Crushing of boards by custom-made crushers
Computer printer	• Motor • Plastics • Cartridge	• Dismantling using screw drivers
Cables and wires	Copper, aluminum	• Incineration or stripping
Computer hard disk, floppy drive, and power supply (SNPS)	Copper and brass alloys, aluminum, iron, and magnet	• Melted after manual separation of each part
Capacitor and condensers	Aluminum	Incineration to extract metallic part

Table 3. Techniques and tools used for e-waste recovery.

traces), as explained. However, the recovery of the said elements may be feasible if large quantities of concentrated e-waste are processed for recovery, deploying suitably advanced technology by striking a balance between desirable recovery vs. yield.

The recycling/recovery of valuable substances by industries in the organized sector with access to requisite technology and manpower is carried out in protected environment, adopting adequate preventive methodology to minimize damage to life and environment. The merit of a focused approach by the stakeholders factually complements the efficacious recovery of metals, including rare and precious metals present in traces, aided by advanced process technology, wherein the processing capacity or volume plays a pivotal role in contributing to the viability aspect, keeping in mind the high cost of capital investments for infrastructure

built-up and affordability for accessing technology advancements in the sphere. Every stakeholder across the board, especially the government policy makers, the scientific community, the industry engaged in the trade, and the society at large, need to introspect at depth and contribute proactively with their respective contribution. This is imperative for arresting the crisis-ridden scenario with tangible solutions, apart from putting forth their best of efforts for raising the consciousness level in the society.

6.1. Authorized e-waste recyclers/reprocessors registered with central pollution control board

For a developing country such as India, long identified as a potential scavenger of the developed world's discarded waste, we have now embarked on a path to discard this concept and identity, at the earliest. This is abundantly clear from the swift and quiet banning of a whole host of imports, including e-waste from overseas, and this per se serves the purpose of putting in place a multi-pronged waste management ethos in the country by regulatory enforcements for productive utilization of domestic e-waste, as generated. Majority of the e-waste in India is channelised through the unorganized sector, and on the flip side, the organized recyclers are battling grossly inadequate input materials for recycling. In order to address the issue, the MoEF had introduced adequate safeguard clauses in the Hazardous Wastes (Management Handling & Transboundary Movement) Rules, 2008 [65]. The MoEF had advised all the government departments/offices that e-wastes generated in various offices and establishments need to be essentially disposed off in an environmentally safe and sound manner, in accordance with the extant rules. The occupiers are now accountable for environmentally safe and sound handling of such hazardous wastes generated in their establishments. The MoEF has notified E-waste (Management and Handling) Rules, 2011 on 1st May, 2012 to provide collection, handling, storage, dismantling, and recycling facilities. CPCB has notified guidelines for implementation of e-wastes rules 2011 and also a list of registered e-waste recyclers/dismantlers, that are in possession of e-waste recycling capabilities [66]. As of November 2014, there were a total of 138 registered e-waste recyclers/dismantlers with CPCB in the country that have recycling/dismantling capacity of 349,154.6 metric ton per annum (MTA) for environmentally sound management of e-waste [67].

6.2. Existence of e-waste recycling plants in India

6.2.1. E-Parisara Pvt. Ltd

E-Parisara, an eco-friendly e-waste recycling unit on the outskirts of Bengaluru, has the capacity to recycle 3 tons of e-waste every day and is expected to be scaled up to achieve a 10-ton capacity in five years [68, 69]. The plant, which is India's first scientific e-waste recycling unit, will reduce pollution, landfill waste, and recover valuable metals, plastics, and glass from waste in an eco-friendly manner. E-parisara works on manual dismantling and segregation, and it separates the materials containing toxic heavy metals such as cadmium, lead, mercury, and so on. Plastic and glass wastes are sold to recyclers authorized by Karnataka State Pollution Control Board (KSPCB) [69]. The metal content can be safely recycled and reused for other processes, while the dust and other wastes can be safely land filled [69]. The process of recycling

involves non-incineration technology, consisting of manual dismantling, segregation, shredding, crushing, pulverizing, and density separation, which includes crushing assured destruction, precious metal recovery, and consumer-friendly methodology [70]. E-parisara Pvt. Ltd. has shared its data of industrial operation, which indicates that 1ton of computers can recover 20kg of ferrous and 29kg of non-ferrous metals, 50kg of cable, and 40kg of PCBs [6]. The volume and cost of the metals recovered from 1 ton of PCBs are indicated in Table 4.

Recovered metal	Weight	Approximate cost (in US$)
Gold	279.93 g	6115 (@ 685.00 per 31 g)
Precious metals (Pt, Pd, In)	93.31 g	3852 (@ 1284.00 per 31 g)
Copper	190.512 Kg	1470 (@ 3.50 per 453.59 g)
Aluminum	142.152 Kg	448.00 (@ 1.28 per 453.59 g)
Lead and Tin (Pb/Sn)	30.844 Kg	144.16 (@ 2.12 per 453.59 g)
Silver	450 g	213.15 (@ 14.70 per 31 g)

NB: Data recovered on average recovery of one ton of populated PCBs and value is taken from the prevailing rate at that point of time. These are only to give a perception of value from the metal recovery from e-waste.

Table 4. Market value of the metal recovered from 1000 kg of PCBs.

E-Parisara has developed a low-cost circuit to extend the life of tube lights. The circuit helps to extend the life of fluorescent tubes by more than 2000+ hours and can also function at low voltage supply of less than 180 V. It can also be used for fused CFLs (compact fluorescent lamps). No starter is required for these tubes, only regular choke is used [69]. E-Parisara also acquired an export license and for the first time sent a consignment of e-waste to Umicore Precious Metals Refining in Belgium. Umicore operates as one of the world's largest precious metals recycling facility [30]. E-parisara not only recycles wastes in an efficient manner but also provides employment opportunities to the rural and unorganized population and creates public awareness by setting up e-waste collection boxes in and around educational institutions and public places [71].

6.2.2. Ash recyclers

Ash Recyclers is a Bengaluru-based environmentally compliant electronic waste recycling organization, which received KSPCB authorisation at around the same time as E-parisara in 2005. Their e-waste recycling and disposal solution consists of creating a balanced mix of reusing and recycling e-waste in order to arrest, to a very large extent, the damaging life and environmental impact while maximizing value addition from the processing of e-waste, which serves the purpose of converting waste to wealth. It is known to encourage second-hand sale through retrieval of working components and refurbishing of old equipment through manual segregation of reusable components and dismantling of e-wastes to recover useful raw materials, in a reasonably controlled environment [69]. They are now in the process of setting

up a new plant for e-waste management (including hydro metallurgical operations) in Mulbagal, about 120 kms from Bengaluru.

6.2.3. K.G. Nandini Enterprises

K.G. Nandini Enterprises (KGN) has started operations in Bengaluru and is India's first fully integrated electronic waste recycling plant [72]. The plant is located in Bidadi and has a capacity of 1ton per hour. KGN has taken the license for a capacity of 7200 MT/annum and does accept all kind of e-waste (PCBs, computers, electric cables, electric transformers, small house hold appliances, etc.). In a first step, hazardous wastes or elements are removed manually at the loading point of the plant comprising the shredder. The reduced material then passes through a magnet where Fe parts are removed. Thereafter, the material enters the delamination mill, which is the heart of the process. Very high impact forces affect the composite materials, leading to reduction and delaminated as well. The material is pneumatically transported from the mill to a cyclone, which, after discharge, is transferred to a screening machine. The classified material is subsequently introduced into a battery of separators, wherein non-ferrous metals are separated from plastics. All process steps are interconnected by an automated, visually-monitored conveying system. A central filter system, which is equipped with explosion and fire safety measures, de-dust the entire process. The equipment reflects the state-of-the-art technology that had been developed and provided by swissRTec AG from Switzerland.

7. Existing e-waste recycling technologies

The recycling methodology broadly comprises of shredding, sorting, grading, compacting, baling, or processing segregated plastics and metal components, followed by separation, identification, and testing as relevant. However, on account of non-availability of suitable recovery technology in the country for some valuable elements such as palladium (Pd), tantalum (Ta), indium (In), gallium (Ga), beryllium (Be), etc., present in traces, the processing of populated PCB components are outsourced overseas at present, despite its significant economic potential and value addition prospect. Evolving suitable scientific technology alone can facilitate the recovery of the valuable elements from the waste PCBs, subject to the availability of large amount of concentrated e-waste containing the said elements.

7.1. CRT recycling

The risk-prone consequence and intense cost implications associated with the disposal of obsolete or malfunctioning CRTs containing highly toxic and hazardous materials such as lead, cadmium, mercury, etc., poses a severe threat to the region. Two major constituents of CRT comprises of glass components (viz., funnel glass, panel glass, solder glass, neck) and non-glass components (viz., plastics, steel, copper, electron gun, phosphor coating), wherein, the CRT glass components consists of SiO_2, NaO, CaO, coloring, oxidizing and X-ray protection components (K_2O, MgO, ZnO, BaO, PbO) and the lead content (Pb) in CRT entails safe handling for its disposal to avert the contaminating impact on air, soil, and ground-water. The glass-to-glass and glass-to-lead recycling, being the two technology route available at present for CRT

(generated from obsolete computer monitors, television, etc.) recycling, converting the old to new CRT glass, happens to be the preferred option, as of date, wherein, isolating the CRT cover needs to be removed prior to depressurization of the CRTs at the Materials Recycling Facility (MRF). Preceding dispatch to CRT recyclers for glass-to-glass or glass-to-lead recycling, separation of metals and shredding of plastics is a processing essentiality.

It is an economical process as compared to smelting, which prevents hazardous waste landfills as well has been successfully evolved for recycling of CRT by Envirocycle–USA, wherein, absterged and sorted glass is utilized as a feedstock in manufacturing new CRT glass by the glass manufacturers, the eventual capacity constraints in processing, however, poses a major disadvantage. In Germany, the unidentifiable glasses are used as productive recycling avenues such as in mines filling, producing sandpaper for scrubbing, the striking surface on match-boxes, etc. Cent-percent conversion of all recyclable components in commercial exploitation and value addition is adopted by PERDI (a company in the USA), wherein, CRT glass is recycled 100% into CLEAN-BLAST sandblasting aggregate for detoxification of lead paints. Circuit boards are outsourced to vendors overseas for recovering valuable and non-ferrous metals. Copper reclaimed from insulated wires, plastic sorted and processed into 'regrind' for utilizing in conjunction with virgin plastic for conversion to new products. Polystyrene recycled into stuffing for new products, corrugated boxes baled and outsourced for producing insulation stuff and cartons. The sheet metal and other ferrous metals are sent to steel mills for smelting and re-used to enter the new production line.

7.2. Glass-to-glass recycling

Glass-to-glass recycling is considered a closed loop process where the collected glass serves as the feed material for producing new CRTs. After the separation of metals, whole glass is ground into cullet without isolating the panel and funnel glass and the said cullet is used for manufacturing new CRTs; however, the disadvantage associated to unknown lead composition in mixed grinding cullet on account of varied CRT glass compositions depending on the manufacturer and its origin, especially for paneled glass is a potential risk. The deployment of a special sawing method or tool to separate the paneled glass from funnel glass prevents the breakage of the paneled glass, thereby keeping it intact and identifiable in contrast to the conventional method of simultaneous breaking of all glass components leading to a mix, is a sustainable approach in reducing risk of contamination [73].

7.3. Glass-to-lead recycling

In the glass-to-lead recycling process, metallic lead (Pb) and copper (Cu) are separated and recovered from the CRT glass through a smelting process. Variably, CRTs generally contain 0.5–5kg of lead (in the glass) [74], which is a potential deterrent against X-ray emission exposure. The recovered CRT glasses processed in the lead smelter also acts as a fluxing agent in the smelting process. This process is automated with high overall throughput and is also cost effective as compared with the glass-to-glass recycling process, apart from protecting the work force from hazardous lead dust contamination on account of the automated nature and its inherent emission control system, the deteriorating value of quality glass, however, is a disadvantage.

7.4. Metals recovery

The separation of metallic components through magnetic and eddy current separators are in vogue, wherein, ferrous components are separated, aided either by a permanent magnet or electromagnet, while metals such as aluminum and copper from non-metallic materials are separated in eddy current separator. Table 5 shows the materials that can be separated by eddy current separator. The main separation criteria is σ/ϱ [75]. On the basis of information provided by the Union Miniere Company [14], Figure 7 presents a copper-smelting flowsheet for recycling of scrap IC boards that is ideally carried out in a primary copper smelting plant, however, such facilities are not well-established in most parts of the world. Thus, removal of the non-recyclable materials (e.g., epoxy resin and fiber glass) from the IC board to enhance the value of recyclable material is preferable since post-separation provides higher metal concentration in lesser volume, thereafter the enriched metal content can then be sold and transported to an appropriate recycling facility for further processing [14].

Metal	σ	ϱ	σ/ϱ	Metal	σ	ϱ	σ/ϱ
Al	0.35	2.7	13.1	**Cu**	0.59	8.9	6.6
Zn	0.17	7.1	2.4	**Brass**	0.14	8.5	1.7
Ag	0.63	10.5	6.0	**Pb**	0.05	11.3	0.4

ρ: density (10^3 kg/m^3), σ: electrical conductivity of material ($10^{-8}/\Omega$m).

Table 5. σ/ϱ values for some metals.

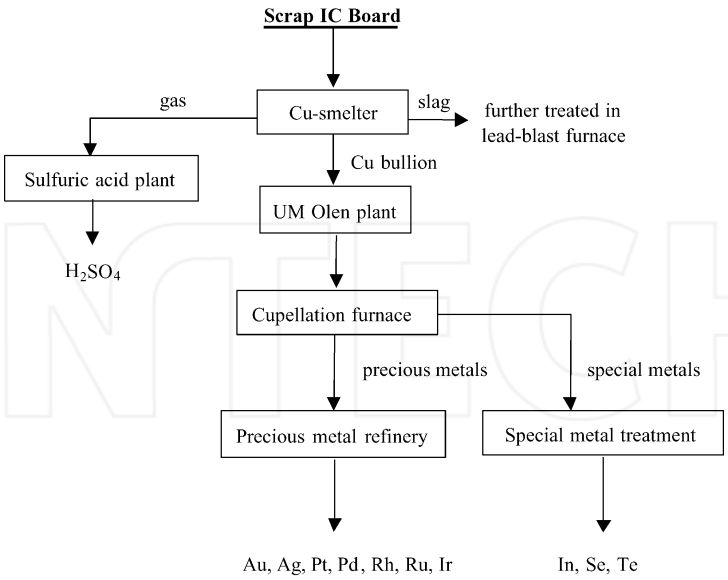

Figure 7. Union Miniere Company's copper-smelting flowsheet for recycling of scrap IC board [14].

Generally, this type of separation plant comprises of a series of physical treatment units devoted to processes such as crushing, grinding, screening, magnetic separation, air classification, eddy-current separation, electrical-conductivity separation, etc., wherein varied metal fragments of various size and content are obtained, depending on the separation technique and units deployed. The varied metal fragments, except iron, usually contain multiple types of metals, thus, identifying appropriate recycling markets for such mixed metal fragments is imperative [14]. There being no necessity of either water or chemical additive in the processing method, there is no wastewater-associated pollution issue, however, special attention should be provided with respect to dust and noise pollution. The low capital and operational cost in a physical separation plant for IC board recycling, being much less compared with a copper-smelting plant, is undoubtedly an added advantage of immense significance. On the basis of information provided by Huei-Chia-Dien Company, Taiwan [14], Figure 8 presents a physical separation flowsheet for the recycling of scrap IC boards.

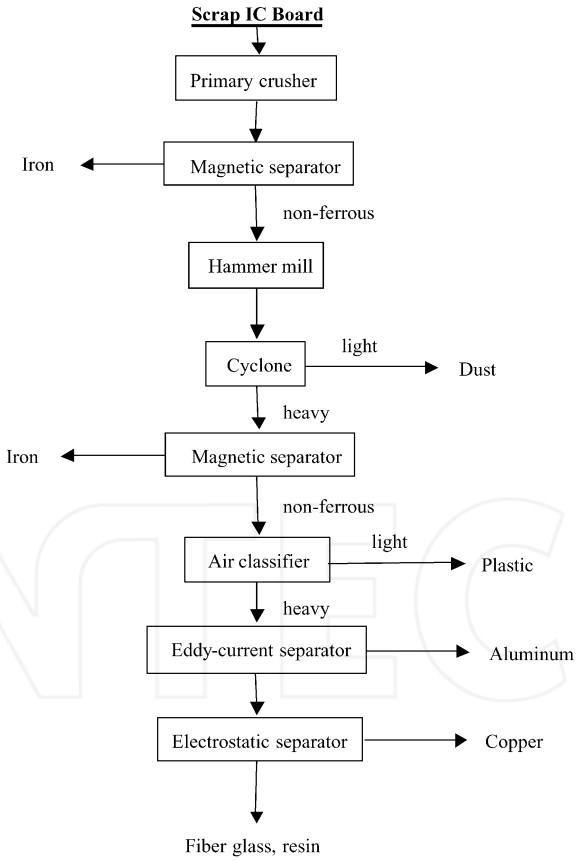

Figure 8. Huei-Chia-Dien Company's physical separation flowsheet for recycling of scrap IC boards [14].

Processing technology has been successfully developed for the recycle and reuse of e-waste at Council of Scientific and Industrial Research–National Metallurgical Laboratory (CSIR-NML), Jamshedpur, India, in which metal bearing e-waste components were shredded and pulverized at the initial operation stage. Subsequently, the metals are separated from the plastics in the particulate mass, adopting a series of physical separation processes. The process does not require much specialized and sophisticated equipment for processing of waste PCBs, since the said equipment and machinery required are readily available, however, its efficiency, especially with respect to commercial viability needs to be further worked upon [76].

The natural hydrophobicity of non-metallic constituents is effectively exploited by a flotation process and a continuous operation at plant level can reasonably be expected to minimize the loss of ultrafine metal values to a negligible level. The operation is simple and the overall processing cost is low, taking into account the comparatively inexpensive physical separation processes deployed. The techniques used are purely physical in nature and thus generate no additional harmful effluents. The process enables the recovery of both metallic and non-metallic constituents separately. Pilot plant scale demonstration was done to recover precious metals from 1 metric ton of e-waste with a recovery rate of 95%. The process flow chart developed for precious metals is depicted in the Figure 9 [39, 77]. Very recently, metal extraction processes from e-waste, particularly the existing industrial practices and routes, have been reviewed [78].

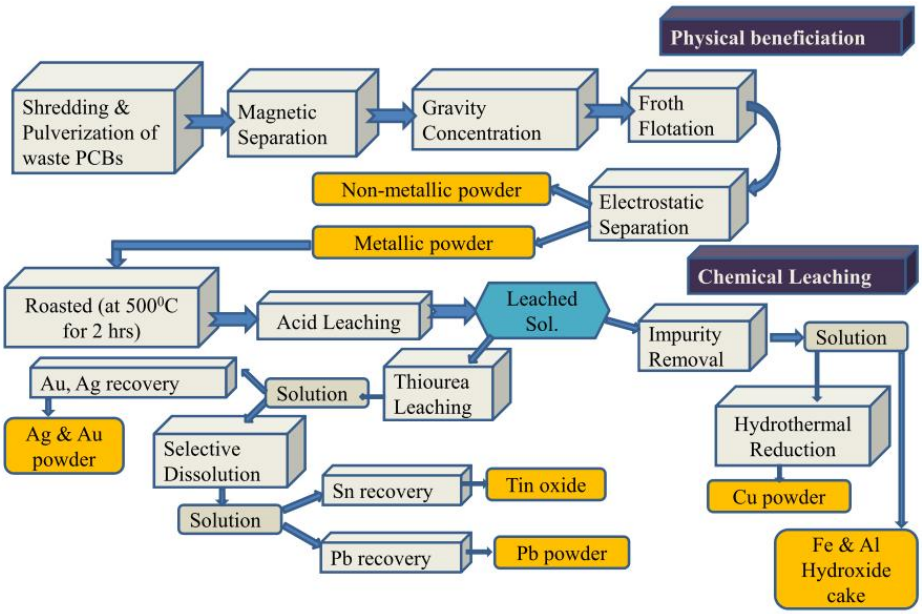

Figure 9. Process flow chart for the technology developed for precious metals at CSIR-NML, Jamshedpur [77].

7.5. Precious metals recovery

In the precious metals refinery setup, gold, silver, palladium and platinum are recovered. The anode slime from the copper electrolysis process is subjected to pressure leaching, followed by drying of the leach residue and the same after addition of fluxes is smelted in a precious metals furnace, leading to the recovery of selenium. The remaining material, primarily silver, is cast into a silver anode, subsequently when subjected to a high-intensity electrolytic refining process, a high-purity silver cathode and anode gold slime are formed while leaching of anode gold slime leads to precipitation of high-purity gold, as well as palladium and platinum sludge. Figure 10 shows the precious metals recovery process. Recovery of precious metals from electronic scraps factually is the key to its commercial exploitation by the recycling industry, for profiteering, in the backdrop of the fact that e-scrap contains more than 40 times the concentration of gold content in gold ores found in the US [79], which is almost one-third the precious metal recovered in e-waste processing. The extraction of the precious metal is carried out by the well-established techniques that are discussed in detail in various articles [80–83]. Various methodologies such as pyrometallurgy, hydrometallurgy, and bi-hydrometallurgy technologies are analyzed for the recovery of gold and also the evaluation of recovery efficiency of gold from e-waste has been reviewed [84].

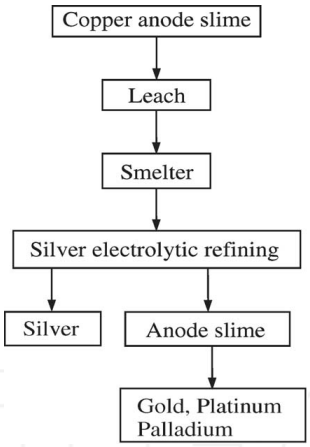

Figure 10. Precious metals recovery process [17].

7.6. Recovery of metals by pyro- and hydrometallurgical processing

Pyrometallurgical processing techniques, including conflagrating, smelting in a plasma arc furnace, drossing, sintering, melting, and varied reactions in a gas phase at high temperatures for recovering non-ferrous metals, as well as precious metals from e-waste, happens to be the conventional method deployed in the past two decades, wherein, the crushed scraps are liquefied in a furnace or in a molten bath to remove plastics and in the process, the refractory oxides form a slag phase together with some metal oxides.

From the process review undertaken by Cui and Zhang [5] with respect to recovering metals from e-waste, the emerging view indicates that both hydro- and pyrometallurgical processes were evaluated in-depth and discussed at length. The process review suggests that hydrometallurgical processes have certain benefits and merit as well when compared with pyrometallurgical processes on account of it being less of a hypothesis or more exact, predictable while also being advantageous from the view point of its ease in control [5]. On the flip side, though hydrometallurgical routes have been adopted successfully to recover PMs from e-waste, from the efficacy perspective, these processes are attributable to certain limiting disadvantages including but not limited to scale-up constraints, which poses to be deterrent to their application at the industrial scale. The review suggests that pyrometallurgical routes are comparatively more economical, eco-efficient, apart from being advantageous from the perspective of maximizing the recovery of PMs [5].

Veldbuizen and Sippel [85] reported the Noranda process at Quebec, Canada as illustrated in Figure 11. The smelter recycles about 100,000 tons of used electronic waste per year, representing 14% of total throughput while the balance percentage comprises mostly of mined copper concentrates. Materials entering the reactor are immersed in a molten metal bath (1250 °C), which is churned by a mixture of supercharged air (up to 39% oxygen), effectively reducing energy consumption in the process since the same is compensated by the energy produced through combustion of plastics and other inflammable materials in feeding. In the process, impurities including iron, lead, and zinc are converted to oxides, forming silica-based slag aided by the agitated oxidation zone, followed by cooling and milling of the slag for further recovery of metals prior to its disposal. The precious metals content of the copper matte is removed before being transferred to the converters, which after upgrade yields liquid blister copper, and this after further refinement in anode furnaces is cast into anodes with purity as high as 99.1%. The precious metals, including gold, silver, platinum, and palladium, along with other recoverable metals, such as selenium, tellurium, and nickel constitute the balance of 0.9%, which is recovered through electro-refining process of the anodes.

Pyrometallurgical processing for the recovery of metals from e-waste is applied by Boliden Ltd. Rönnskar Smelter, Sweden [31]. Purity-linked multiple step feeding of e-scraps, is illustrated in Figure 12. The scraps with high copper content scrap is processed in the Kaldo Furnace and around 100,000 tons of scraps including e-waste was reportedly being processed in the Kaldo Furnace year-on-year, as per an APME report during the year 2000. E-waste blended with lead concentrates is processed in a Kaldo rector with skip-hoist assisted feeding [86] and the required oxygen for combustion in oil-oxygen burner is provided through an oxygen lance in the system, while off-gases are subjected to additional combustion air at around 1200 °C post-combustion. A standard gas handling system recovers thermal energy assisted by a suitably configured steam network. The mixed copper alloy produced by the Kaldo Furnace is processed in a copper converter for recovery of metals (Cu, Ag, Au, Pd, Ni, Se, and Zn), while the dust content (containing Pb, Sb, In, and Cd) is subjected to other processing operations for the recovery of relevant metal content. However, the publications lack detailed discussions on environmental issues, such as emission of pollutants in air and water.

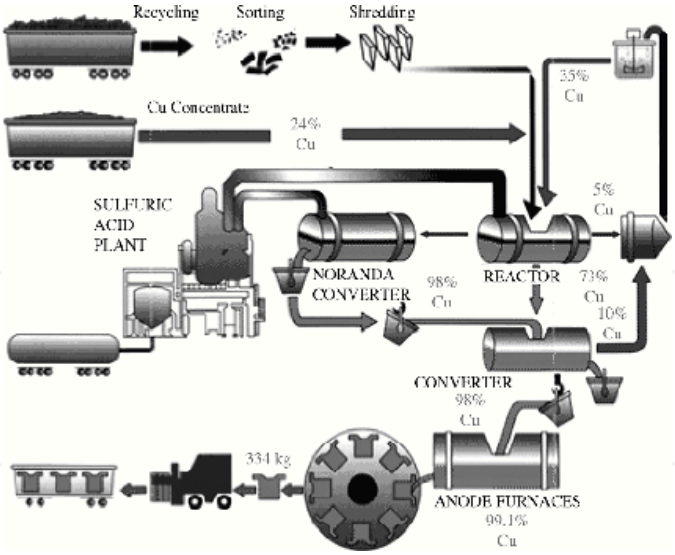

Figure 11. Schematic diagram for the Noranda Smelting Processing [85].

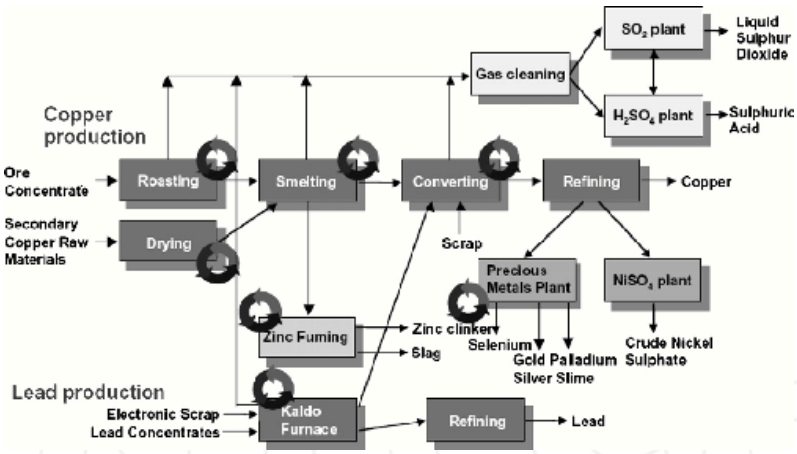

Figure 12. Schematic diagram for the Rönnskar Smelter [31].

Umicore published [30, 87] its precious metals refining process at Hoboken, Belgium, which is primarily focused on the recovery of precious metals from e-waste. Various industrial wastes and by-products from other non-ferrous industries (e.g., drosses, matters, speiss, anode slimes), sweeps of precious metals and bullions, spent industrial catalysts, as well as consumer recyclables such as car exhaust catalysts or PCBs are acceptable for the integrated metals smelter and refinery process. The plant treats around 2,50,000 tons of varied wastes per annual,

out of which electronic waste presently comprises up to 10% of the feed [30]. It is the world's largest precious metals recycling facility with a capacity of over 50 tons of PGMs, over 100 tons of gold, and 2400 tons of silver [88]. The first step in the precious metals operations (PMO) is smelting by using an IsaSmelt furnace. Plastics or other organic substances that are contained in the feed partially substitute the coke as a reducing agent and energy source. The smelter separates precious metals in copper bullion from most other metals concentrated in a lead slag, which are further treated at the Base Metals Operations (BMO). The copper bullion is subsequently treated by copper-leaching and electrowinning and precious metals refinery for copper and precious metals recovery.

The Base Metals Operations process by-products from the PMO. The main processing steps are lead blast furnace, lead refinery, and special metals plant. The lead blast furnace reduces the oxidized lead slag from the IsaSmelt together with high lead-containing lead bullion, nickel speiss, copper matte and depleted slag. The impure lead bullion, collecting most of the non-precious metals, is further treated in the lead refinery (Harris process). Special metals (indium, selenium, and tellurium) residues were reported [30] to be generated in the lead refining process. Consequently, pure metals are recovered in a special metals refinery. In the Umicore's plant, following complex flowsheet with several steps including pyrometallurgical techniques, hydrometallurgical process, and electrochemical technology are employed in the recovery of base metals, precious metals, as well as platinum group metals and special metals are shown in Figure 13 [87].

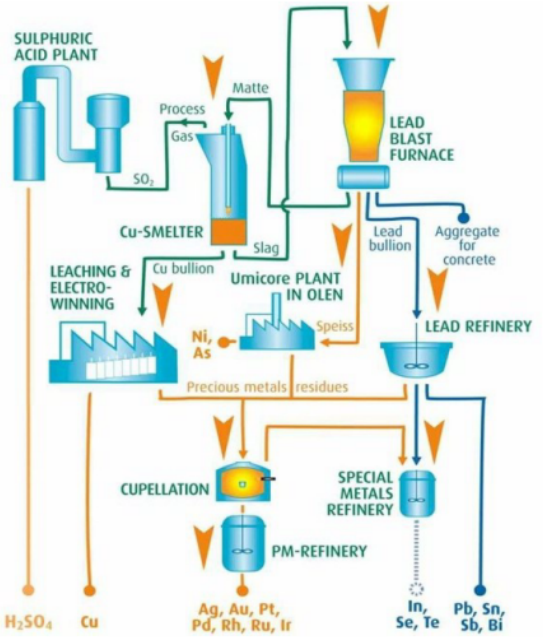

Figure 13. Flowsheet for Umicore's integrated metals smelter and refinery [30].

7.7. Composition and recovery of metal value from scrap mobile phones

The content or substances in cellular phone are variable to some extent, based on the model and its manufacturer, with no fixed formula or list of contents applicable as such, thus, the list of substances in an average mobile phone may also be misleading since varied substances might be used as additives in very minimal quantities or traces by different manufacturers in the production of microelectronic components. However, the general composition of cellular phones and other small electronic goods as well, is identical in nature. Table 6 presents the fractional composition of a modern cell phone [89]. Recovering metals of higher percentage concentration like copper and metals of precious value or worth like gold, palladium and silver is factually the underlying objective for metal recovery from EOL or obsolete cellular phones and aluminum or magnesium cases of cellular phones wherever applicable, contribute further to value addition or generation through its recycling.

Cell phones	Plastics	Pb	Al	Fe	Sn	Cu	Ni	Zn	Ag	Si	Hg
Fraction (wt%)	46.0	0.9	9.0	8.0	1.0	19.0	1.0	3.0	0.9	4.0	1.0

Table 6. Fractional compositions of mobile phones.

The flowchart (Figure 14) shows two methods of recycling scrap mobile phones developed in Korea [38]. The first method (process I) involves shredding of waste PCBs and shipment to a copper smelter. The second method (process II) comprises of shredding, conflagration, melting or converting to copper alloy containing precious metals, and subsequent refining adopting the hydrometallurgical route. However, the systemic operation of recycling for e-waste processing operations in Korea does not in true sense function effectively since the majority of waste mobile phones collected are exported or conflagrated and landfilled, while only 2.5% of the waste mobile phones collected are actually processed for recycling. A pilot plant to recover cobalt from spent lithium-ion batteries of waste mobile phones is under operation, taking into account the high-valuation of cobalt.

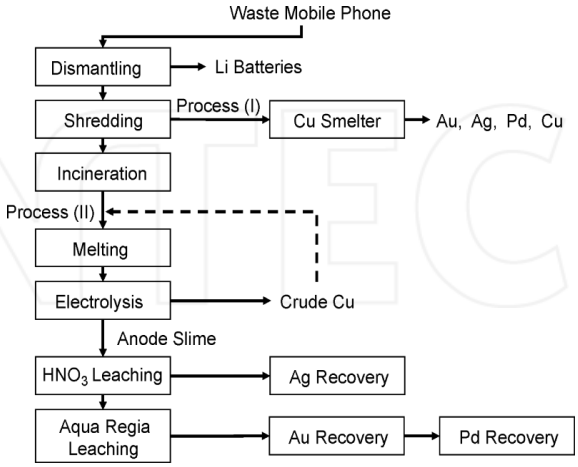

Figure 14. Flow sheet for the recycling of metal values from waste mobile phones in Korea [38].

8. Summary and conclusions

The phenomenal transformation in the lifestyle pattern of consumers of electronic goods, in the emerging scenario, is triggered by their contribution to the convenience and ease in everyday life. This is attributable to the concerted efforts of the global scientific genre, especially focused upon scientific developments in sync with modern era living comforts of the target consumers. Incremental rate of obsolescence and subsequent upgrades of product quality are key psychological impacting factors factually influencing the consumers' mindset in contributing to the faster turnaround of the product life cycle. This aspect is proving to be a potential trigger in accelerating the pace of accumulation of huge EOL-EEEs (e-waste) such as computers, mobile phones, televisions, etc., contributing to the solid waste stream. The said devices contain various non-ferrous and ferrous metals such as lead (Pb), copper (Cu), gold (Au), aluminum (Al), silver (Ag), palladium (pd), which as such gets disposed off as waste, even though it has immense potential of being converted to wealth from waste, including but not limited to serving the purpose of catering to as vital inputs in new product cycle. These valuable and precious metals comprising e-waste, when subjected to processing by the unorganized sector with limited perspective of profit motive, by adopting, more often than not, scientifically unsustainable methodology such as manual sorting, grinding, and incineration, leads to catastrophic environmental implications and health hazard to the workforce as well, especially emanating from its consequent and collective toxic impact of both gas and metal components.

Safe and scientific disposal management with respect to EOL-EEEs continues to remain an uphill task, in both developing and developed countries, and in the process, the former, more often than not, gets cannibalized by the developed countries on account of their illegal and irresponsible approach of shipping the same to developing countries, as an easy escape. Advancement in technology for the sustainable recovery of valuable materials from e-waste needs to be an evolving process to resolve this escalating problem with respect to environment and life. However, usage of the technology comprises many processing techniques of thermal processing, bioleaching, hydrometallurgy, pyrometallurgy, etc., deployment of which is interdependent upon the intended processing and recovery objective, commercial feasibility of the process involved, mandatory and regulatory issues in place, etc. The developing countries as well are gradually tightening the enforcement of regulatory norms in facing the challenges ahead, apart from the developing countries in the European Union, for sustainable, eco-friendly handling, collection, and disposal of e-waste. As is known, the developed countries have technology and infrastructure superiority, the developing countries, on the other hand, have the advantage of economy with respect to labor cost, considerably impacting both handling and processing cost and the prospect of accomplishing a win-win situation based on one's inherent strength or advantages has the potential for being commercially exploited with scientific temperament, complement each other in making this world a safer habitat.

The conventional methods of e-waste management by disposing in landfills or incineration or exporting to developing or underdeveloped countries are becoming redundant since this is already in the process of being banned in absolute terms with consciousness about its hazardous and life-threatening implications dawning upon the stakeholders, with passage of time, which to some extent is also influenced by print and media. This can be furthered by active interaction between the scientific community and the stakeholders, including the industry and public at large, since it is ethically incumbent upon the scientists to play their role in arresting the highly detrimental consequences to nature and life. Stringent and mandatory norms are being put into place, even by the underdeveloped countries, for protecting its citizens and the environment, contrary to the slackness that earlier existed, thereby exposing to exploitation by the developed countries. The presence of precious metals in e-waste recycling makes it an immensely attractive business potential, both in terms of environment and economics. There is need for evolving fool-proof solution, which addresses the limitations of current technologies, provides accessible and comparatively cost-effective techniques, efficient and eco-friendly methodologies in addressing the menacingly escalating threat to environment and life, including but not limited to the carcinogenic impact of the toxins released in crude processing of e-waste. CSIR-NML has developed a processing technology with certain advantages vis-à-vis conventional techniques with respect to metal recovery from EOL-EEEs and the laboratory is looking for interested parties for further investigation, development, and commercialization of this technology-based solution.

Increased public awareness and active participation among stakeholders across the board, including government and regulatory authorities about the damaging implications of crude recycling processes borne out of unscrupulous profit motive and incentivise the tremendous business potential of environmentally safe recycling through sustainable methodology, based on scientific techniques, is essentially imperative. Focused participation and change in mindset among all stakeholders including the industry and inhabitants at large for tangible accomplishment of the "two-pronged" intended goal and objective is unequivocally essential from larger perspective, i.e., safe and sustainable recycling while converting waste to wealth in adding to the country's economy.

Keeping in mind the rapidly escalating scenario and change in lifestyle pattern, future safety with respect to environment and life, evolving sustainable and scientific e-waste management in a focused manner with sufficient infrastructure and financial resources is imperative. On the other hand, evolving effective legislations and monitoring mechanisms for enforcement of the same by countries is equally vital, in accomplishing the herculean task that lies ahead.

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