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REVIEW ARTICLE

Sustainability of metal recovery from E-waste

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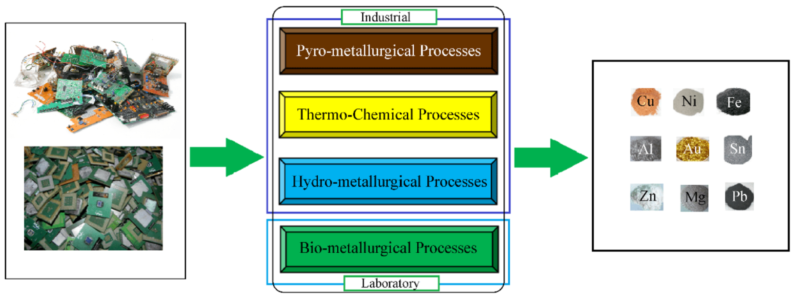
HIGHLIGHTS

- Metal recovery techniques from electronic waste reported in literature.
- Metal recovery processes followed in Industries from electronic waste.
- Sustainability analysis of metal recovery processes from electronic waste.

GRAPHIC ABSTRACT



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ABSTRACT

The issue of E-waste disposal is concerning all the stakeholders, from policymakers to the end users which have accelerated the research and development on environmentally sound disposal of E-waste. The recovery of metals (gold, tantalum, copper, iron etc.) from E-waste has become an important focus. The mechanical recycling, thermo-chemical processes like pyrolysis, pyro-, hydro- and bio-metallurgical processes can play important roles in the Metal Recovery from E-waste (MREW) technology. For the industrial application of the MREW technology, it is important to analyze the sustainability. In this paper, two case studies have been presented on E-waste recycling industries in India and China. Based on the literature data, an attempt has been made to assess qualitatively the overall sustainability of MREW technology considering the three pillars, i.e., environmental, economic and social. Two conceptual frameworks with (Option–2) and without (Option–1) pyrolysis for integrated MREW units have been developed and the generalized energy and environmental impact analysis has been made using the principles of LCA. The impacts of two options have been compared. Option 2 has been found to be more efficient and sustainable. It has been realized that climate change, fossil fuel depletion, water depletion, eutrophication, acidification, fresh and marine water ecotoxicity are possible impact categories. The recommendations based on the generalized assessment are in good agreement with the findings of previous researchers on individual steps of MREW unit. The findings of this paper are expected to be beneficial to researchers and stakeholders for research directions and decision making on MREW.

1 Introduction

The Electrical and Electronics Equipment (EEE) industry is one of the largest industries in the world. The electronic industry is expected to reach $400 billion in 2022 from $69.6 billion in 2012 (Corporate Catalyst India 2015). The demand of EEE is ever increasing and the driving force behind this demand is often the technological advancement coupled with short innovation cycles and business strategies which shortens the lifespan of the equipments. E-waste generation is increasing exponentially every year. Huisman (2010) predicted that E-waste generation will be 19.1 kg/person/year by 2012 in 27 EU countries leading to total 10.5 million tons of E-waste by 2014. In 2014, the

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worldwide generation of E-waste is 41.8 million metric tons and by the year 2018 it is expected to rise by 21% to 50 million tonnes (McMahon, 2016). In 2015, nearly 54 million tons of E-waste was produced globally. BRICS nations generated nearly 25% of the total E-waste generated in 2014 (Ghosh et al., 2016). Associated Chambers of Commerce of India (ASSOCHAM) reported that India generated 1.5 million tons of E-waste in the year 2015. The E-waste generation in China was estimated to be 6.033 million tonnes in 2014 (Baldé et al., 2015).

Different strategies like Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Extended Producer Responsibility (EPR), Advanced Recycling Fee (ARF) etc. have been introduced for E-waste management and mostly, these have been implemented in the developed nations. However, till date recycling of E-waste is considered to be the best approach for E-waste management. While the primary resources are depleting, metals from E-waste could be an important source and Metal Recovery from E-waste (MREW) could be a potential opportunity of metal recovery from secondary resources. High content of base metal (Fe, Cu, Al, Pb and Ni) and precious metal (Ag, Au, Pt and Pd) present in E-waste results makes it a potential source of secondary resources for metal recovery. Typical metal composition of printed circuit board is presented in Table 1 and Table 2. The metal content of E-waste varies widely depending on the type of E-waste. Debnath et al. (2016) has shown in their study that the metal content in different E-waste is different based on size and operation. For example, keyboards contain 95% polymer whereas the printed circuit boards are rich in metals. Printed Circuit Boards (PCB) from a typical computer contains nearly 20% Cu and 250 mg/ton Gold, whereas the Copper percentage goes down in PCBs from mobile to 13% and Gold goes up to 350 mg/ton (Hagelüken, 2006). The metal content in printed circuit board is higher than the ores/concentrates.

MREW is a lucrative business as well as a very popular area of research. Different conventional techniques like physical processing, pyro-metallurgical processing, hydro-metallurgical and bio-metallurgical processing have been in implementation for metal recovery. Physical or mechanical recycling of E-waste is considered as a pre-treatment process. Metal rich fraction evolving from the pre-treatment are subjected to pyro-metallurgical, hydro-metallurgical and bio-metallurgical processing for selective recovery of metals. Several studies have been reported focusing on metal recovery processes and an extensive number of them focused on comparative review, salient features, strength and weakness of the technologies. Apart from these, for the industrial application of the MREW technology, it is important to analyze the sustainability. On the other hand, there exists a distinct difference between laboratory practices and industrial practices. It is also of importance to look beyond laboratory and find out what is happening in the field. Studies focusing on these aspects have not been observed before in contemporary literature. In this study, an attempt has been made to address those issues.

2 Methodology

First, thorough literature review was undertaken exploring different databases like Science Direct, Google Scholar, Emerald Insight etc. Several keywords such as 'E-waste Recycling', 'Metal recovery from E-waste', 'Printed Circuit Board Recycling', 'Leaching of E-waste', 'Gold recovery from E-waste', 'Sustainability of E-waste recycling' etc. were used in this case. Thereafter, case study organizations were visited and their process operations were understood and reviewed thoroughly. Based on the findings, two conceptual frameworks were developed for integrated MREW. Then a generalized comparative analysis of the two scenarios was carried out from the perspectives of three pillars of sustainability.

3 Metal recovery process from E-waste

Metal recovery from E-waste is a lucrative business opportunity for the small and medium enterprises (SMEs). Many conventional thermo-chemical and bio-chemical processes have been tested both in pilot and laboratory scale for metal recovery from E-waste. Various researchers have used hydro-metallurgical (Kim et al., 2011), pyro-metallurgical (Hall and Williams, 2007) and bio-metallurgical (Ilyas and Lee, 2014) methods for this purpose.

Table 1 Typicalcomposition of basic metals in PCB (E-waste guide info)

Name	Cu	Al	Pb	Zn	Ni	Fe	Sn
Concentration in wt%	6.9287	14.1723	6.2988	2.2046	0.8503	20.4712	1.0078

Table 2 Typicalcomposition of rare earth and valuable metals in PCB (E-waste guide info)

Name	Sb	Au	Ag	Pd	Ga	Ge	As	Ti	Ta	Co	Se	Ni	Cd
wt%	0.0094	0.0016	0.0189	0.0003	0.0013	0.0016	0.0063	0.0157	0.0157	0.0157	0.0016	0.0002	0.0094

However, physical processes for metal recovery are quite in practice for easier operation and lower carbon footprint.

3.1 Physical recycling methods

Physical recycling methods are generally used for upgradation which helps in liberation of metals and non-metals contained in E-waste. To the best of the authors' experience in visiting several E-waste recycling facilities around the globe, physical recycling is the commonly practiced method for recycling E-waste all over the world. When it comes to the metal recovery, this is one of the efficient methods for metal recovery. Often it is considered as one of the pre-treatment step before further processing. Physical recycling includes disassembling, dismantling, chopping, shredding, crushing etc. These steps are achieved by using machineries like shredder, pre-granulator, granulatoretc. After this, the separations of metal from the non-metals are achieved. Different methods such as magnetic separation, eddy current separation and density separation are used (Kang and Schoenung, 2005). It is possible to recover metal fraction containing more than 50% of copper, 24% of tin, and 8% of lead by implementing a combination of electrostatic and magnetic separation which separates the metal part from the non-metal ones (Veit et al., 2005). There are other methods reported in literature such as corona discharge method (Zhang and Forssberg, 1998; Li et al., 2007) (suitable for separation of metallic and non-metallic fractions), density based separatiotn (Peng et al., 2004), milling (Koyanaka et al., 1997), froth floatation (Ogunniyi and Vermaak, 2009; Vidhyadhar and Das, 2012) etc.

3.2 Thermo-chemical methods

When it comes to thermo-chemical processes, pyrolysis is an important process. Pyrolysis is a thermo-chemical process which ensures thermal degradation of a targeted material in absence of air. A significant number of studies have been carried out on pyrolysis of E-waste (Sun et al., 2003; Xiong et al., 2006; Guo et al., 2010).

Vacuum pyrolysis (Qiu et al., 2009), microwave induced pyrolysis (Ruidian et al., 2007; Sun et al., 2012), catalytic pyrolysis (Hall et al., 2008) and co-pyrolysis (with biomass) (Liu et al., 2013) are different types of pyrolysis that has been reported. Though pyrolysis of E-waste is mostly limited within the laboratory, Jectec (a company from Japan) has already implemented pyrolysis in their facility. Another process which has gained attention these days is the plasma process that is being implemented for E-waste treatment and metal recovery. Plasma Technology is a high temperature and environment friendly technology. This is applied in MSW and biomedical waste disposal. Ruj and Chang (2013) reported plasma treatment of mobile phone waste and it showed that the process helps in recovery of metals. High enthalpy plasma jet (Mitrasinovic et al., 2013), plasma reactor (Rath et al. 2012) and plasma torch (Tippayawong and Khongkrapan, 2009) has been explored for processing of E-waste. Despite very small number of available literature, it is already being used industrially in PyroGenesis Canada Inc.

3.3 Pyro-metallurgical methods

Pyro-metallurgical processes are widely employed for MREW around the world. Generally, when the metals are present in a complex matrix with other non-metals and ceramics etc, it is often difficult to recover them implementing the physical recycling processes. In that case, pyro-metallurgical method is the option. Printed circuit boards (PCB) are complex and is easier to recycle using these methods. The PCB's are first shredded or chopped into suitable pieces and then they are subjected to pyro-metallurgical processing. Smelting, refining, incineration, combustion are the common processes in this route. The state-of-art facilities available in the smelting and refining facilities are capable of extracting valuable metals from the complex matrix and are quite efficient (Antrekowitsch et al., 2006; Khaliq et al., 2014). A typical pyro-metallurgical treatment process is smelting followed by electro-chemical refining. First E-waste or metals recovered by physical recycling are fed into the furnace. The metals are collected in a molten bath and the oxides are obtained from the slag phase. Umicore, Outotec TSL, Aurubis recycling are to name a few that employs pyro-metallurgical processes for metal recovery from E-waste (Khaliq et al., 2014).

3.4 Hydro-metallurgical methods

Hydro-metallurgical methods implemented for metal recovery from E-waste are the modified version of the traditional hydro-metallurgical methods used for metal extraction from primary ores. Leaching is carried out by means of acid, alkali or other solvents to leach out metals in form of soluble salts. Impurities are removed with the gangue materials and the isolation of metals from the solution is achieved by processes such as adsorption, solvent extraction etc. Final forms of metals are achieved through electro-refining or chemical reduction processes (Shamsuddin, 1986; Khaliq et al., 2014). Four types of common leaching processes, namely — cyanide leaching (Kolodzziej and Adamski, 1984), halide leaching (Quinet et al., 2005), thiourea leaching (Sheng and Etsell, 2007) and thiosulfate leaching (Chmielewski et al., 1997) are there. Copper and other precious metals such as gold, silver etc can be recovered via hydrometallurgical route and a detailed discussion can be found in the study by Wu and group (2017). Rare Earth Elements (REE) can also be recovered via this route and consolidated studies have been reported (Sun et al., 2016). Aqua regia was used as leaching agent for recovery of gold from printed circuit board (Sheng and Etsell, 2007). Metals such as nickel (Kim et al., 2007), tin (Gibson et al., 2003), copper (Veit et al., 2006), silver (Petter et al., 2014), palladium (Quinet et al., 2005) has been reported to be recovered from E-waste. It was found that nitric acid; sulphuric acid and muriatic acid based solutions are majorly implemented for primary leaching of precious metals from E-waste. Recent focus on tin recycling from E-waste has been found among the researchers (Mecucci and Scott, 2002; Yang et al., 2017a). A green hydrometallurgical process has been developed for recovery of tin from PCBs via co-processing of waste PCBs and spent tin stripping solution which is generated during production of PCBs (Yang et al., 2017b). Umicore uses hydro-metallurgical processes for metal recovery. Industrial applications of such green processes are essential for sustainability.

3.5 Bio-metallurgical processes

Bio-metallurgical processing of E-waste is an emerging and a very promising area. There exist plenty of opportunities for research and development as well as business. Bio-metallurgical processes can be classified into two sections – a) Biosorption and b) Bioleaching. Biosorption means adsorption of metals by means of adsorbents prepared from waste biomass or abundant biomass. Metal recovery from E-waste by biosorption has been achieved by using algae (*Chlorella vulgaris*), fungi (*Aspergillusniger*), bacteria (*Peniciliumchrysogenum*), hen eggshell membrane, ovalbumin, alfalfa etc (Darnall et al.,1986; Kuyucak and Volesky, 1988; Niu and Volesky, 1999). The mechanism associated with biosorption is complex and no clear picture is available. There are certain factors that affect the process — a) Type of biological ligands accessible for metal binding, b) Type of the biosorbent (living, non-living), c) Chemical, stereo-chemical and co-ordination characteristics of the targeted metals and d) Characteristics of the metal solution such as pH and the competing ions (Tsezos et al., 2006).

According to Ilyas and Lee (2014), the mobilization of metal cations from often almost insoluble materials by biological oxidation and complexation processes is referred to as bioleaching. There are three major group of bacteria associated with in bioleaching of E-waste are – a) Autotrophic bacteria (e.g. Thiobacilli sp.), b) Heterotrophic bacteria (e.g. *Pseudomonas* sp., *Bacillus* sp.) and c) Heterotrophic fungi (e.g. *Aspergillus* sp., *Penicillium* sp.) (Schinner and Burgstaller, 1989). Typically bioleaching occurs in four steps — a) Acidolysis, b) Complexolysis, c) Redoxolysis and d) Bioaccumulation (Bosshard et al., 1996). Bioleaching has been explored by researchers for recovery of Gold, Aluminum, Copper, Nickel, Zinc and Lead from E-waste (Brandl et al., 2001; Faramarzi et al., 2004; Alan et al., 2005; Wang et al., 2009; Yang et al. 2009; Bas et al., 2013). There is no example of any industrialized process in the bio-metallurgical route.

4 Case studies

4.1 Case study organization A

Location: Karnataka, India

Capacity: Full recycling capacity of 10 ton/day but currently handing 6 ton /day

Land Area: 1.5 acres of land with 25,000 sq. ft. closed area and 60, 000 sq. ft. of open area

No. of Employees: 100 (50 men + 50 women).

Profitability trend (last five years): High.

This organization is one of the oldest E-waste recycling plants in India. The objective of this unit is to convert E-waste into beneficial raw materials (metals, plastics, glass etc.) by implementing simple, cost effective, indigenous, environmental friendly technologies suitable for Indian conditions. Its products and services includes E-waste collection, dismantling, processing, recycling; metal, plastic, glass and different other recycled products; gold recovery from printed circuit board strips etc.

This company provides the necessary logistics for collection of different types of E-waste through e-auction or direct purchase. The collected E-waste coming from the collection centers and other sources in the facility is recorded in the data entry book in terms of its weight, source and data entry records. All the E-waste is first checked for any radioactive materials before being taken in to the dismantling line/area. Different streams are segregated at the first level before actual pre-processing. The collected E-waste first undergoes manual dismantling. Trained employees with safety equipments uses basic toolkits such as hot air gun, screw driver etc. to efficiently dismantle the E-waste. Separate work tables are allocated for each person. Air suction duct is present in each table which prevents any kind of particulate emission during dismantling. The dismantled parts are further segregated and dismantled into various streams. This facilitates easier operation and efficient processing. The resulting streams are fed to respective machineries for resource recovery and recycling. The basic dismantling results into metal rich parts, printed circuit boards, plastics, wires and CRT. These streams (except CRT and wires) go through mechanical size reduction performed by Shear-shredder and hammer mills. Then density separation is carried out to separate metals and non-metals. Sister companies and other 3rd party industries are in contractual practice for metal recovery and other component recycling.

The company have developed their own process for CRT recycling. The composition and hazardous characteristics of the panel and the funnel glass are different. The recyclability of waste CRTs are substantially increased when the panel and funnel glass are separated and sold to manufacturers. These scraps then can be recycled to produce new panel and funnel glass. Electric wire heating method is used to cut CRT into two halves. This separation also facilitates removal of hazardous fluorescent color

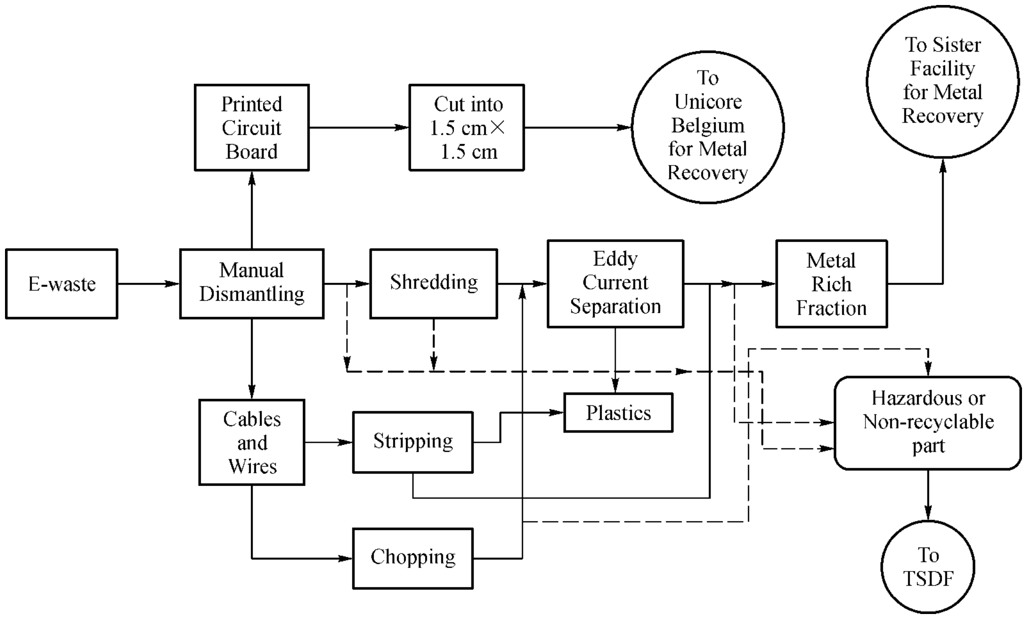

Fig. 1 Process of E-waste recycling in Indian Unit

coating from the surface of the panel glass. *Vacuum-suction method i*s employed for this purpose. The glass is recycled by one of the leading TV manufacturer which uses 30% of the waste glass and rest virgin glass for manufacturing the TV glass panel. For wires, their indigenous stripping machine strips of the metal from the polymer coating. For cables with higher diameter, ranging from 2 mm to 10mm, are manually fed in the inlet holes from one end and longitudinally chopped pieces are collected from the other end, which are further manually segregated and sent to eddy current separator for separation of metals and non-metals.

The company is also associated in a social project where they have employed informal waste collectors and they buy waste printed circuit board (PCB) and other E-waste from them. These PCBs are shredded to 1.5” X-1.5” size for smelting. It exports shredded circuit boards and components for copper smelting to Umicore Precious Melting Refining, Belgium with the approval from Ministry of Environment and Forests. All together it can be commented that this E-waste recycling plant cares about the society and environment and is working for the cleaner environment.

4.2 Case study organization B

Location: Beijing, China

Capacity: 10,000 tons/year

Land Area: 1.5 acres of land with 25,000 sq. ft. closed area and 60, 000 sq. ft. of open area

No. of Employees: 120

Profitability trend (last five years): High.

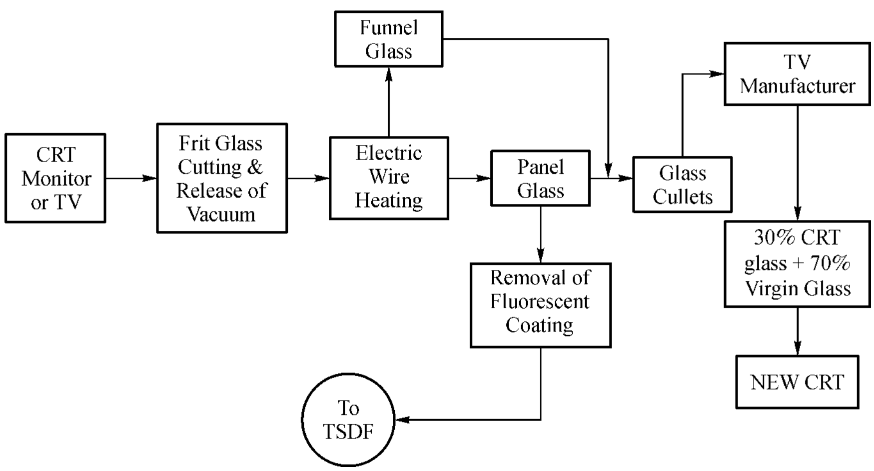

Fig. 2 Process for CRT recycling in Indian Unit

This organization is a model E-waste recycling plant for the city of Beijing, China. The unit provides waste dismantling, recycling service and disassembling E-waste as main competitive products. The company has specialized management team with professional knowledge in this sector committed to quality, honesty and value in E-waste recycling.

In the processing there are manual and semiautomatic sorting, dismantling in the E-waste recycling plant. Then the preprocessed material is sent to the processing stage. The material hence recovered are then reprocessed if required. They have separate line for refrigerators and degassing unit for safe removal of coolants. Then they are coarsely shredded and further crushed before subjecting to magnetic separation and eddy current separation for separation of metal and non-metals. Waste television sets are treated separately to take out the CRTs. The vacuum tube is cut out first. Then the glass panel and the funnel are separated out. The hazardous substances are removed before crushing the glass.

5 Sustainability of MREW technologies

Sustainability analysis of any process requires detailed intervention of the three sustainability parameters i.e. environmental, economic and social. Metal recovery from E-waste is a complex process and the heterogeneity of the material makes it even more complex. It is important to consider all three parameters for evaluation and prediction of the sustainability of metal recovery processes from E-waste. One important observation from the popular literature is that almost all the assessments of sustainability of E-waste processing are focused on determination of environmental impacts via LCA. The economical and the social aspects have been excluded in those studies. A few studies have been identified in the social sector but the focus is on the informal sector. In this section, an effort has been made to give an overview of the sustainability of metal recovery processes from E-waste considering all three parameters of sustainability.

5.1 Generalized discussion on environmental sustainability

Environmental Sustainability of any process is generally characterized by some factors. These factors are assigned with some scores that dictate the magnitude of impact on the environment. A Life Cycle Analysis is arguably the ultimate method to assess environmental sustainability. Metal recovery from E-waste is lucrative as well as complex in nature as the metals are present within the solid polymer matrix of the printed circuit boards. To assess the environmental sustainability of the recovery processes discussed in section 3, it would require a large comparative LCA exercise to be carried out. However, a good number of standalone and comparative LCA exercises have been carried out by researchers. The standalone LCA are either on the whole treatment or technology and/or feed material specific. But the comparative LCA are just two alternatives of similar or with or without pre-treatment of a focused process.

To elucidate on the energy and environmental sustainability of MREW technologies, two conceptual scopes represented in Figs. 4 and 5, have been developed. In option 1, the metallurgical processes of pyro, hydro and bio categories are preceded by pre-treatment operations consisting only of mechanical and gravimetric types. On the other hand, the pre-treatment step is a combination of

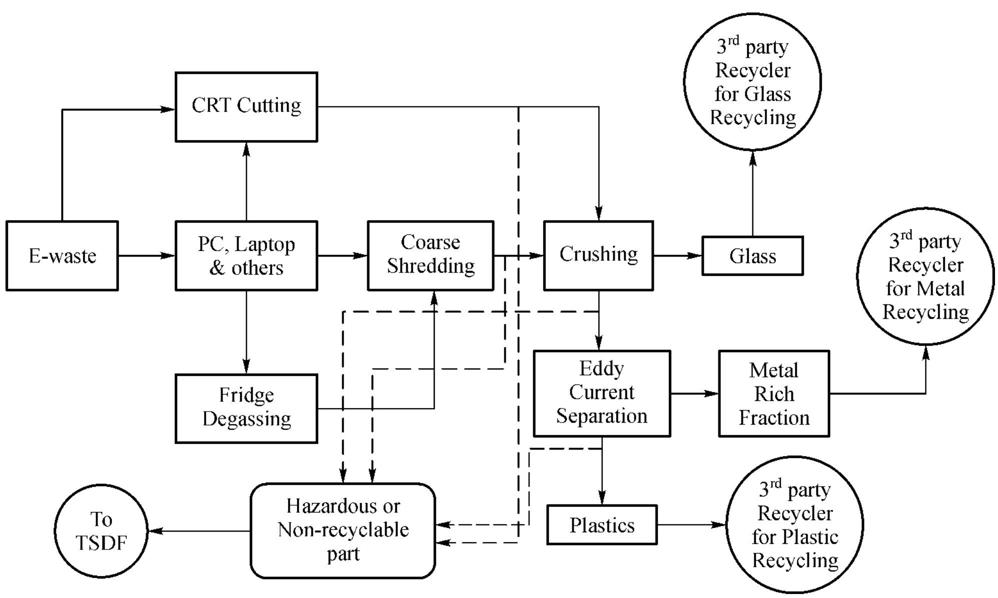

Fig. 3 Process for E-waste recycling in Chinese Unit

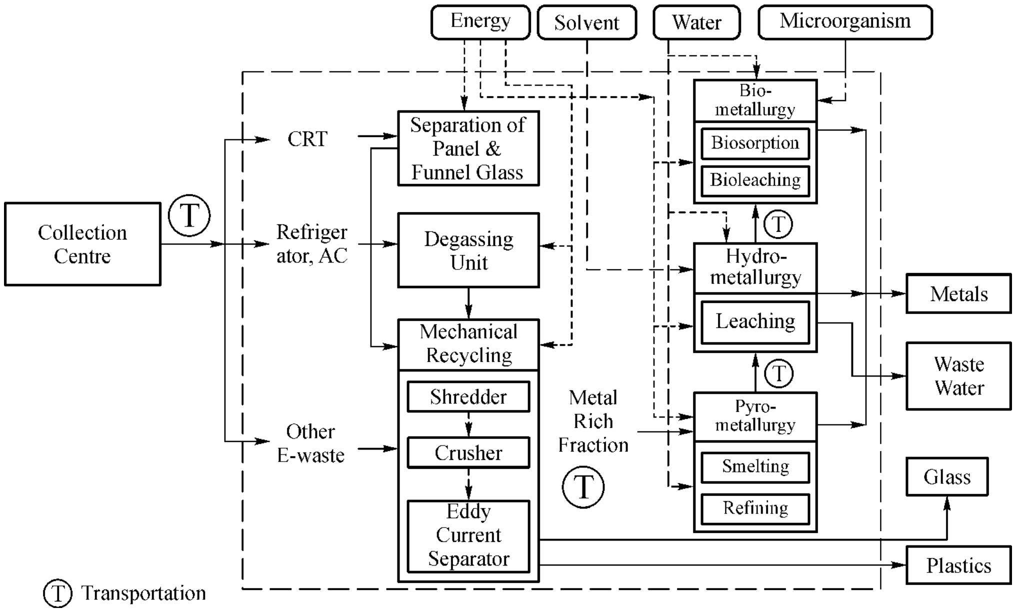

Fig. 4 Conceptual framework with conventional mechanical pre-treatment followed by metallurgical processing for MREW (Option-1)

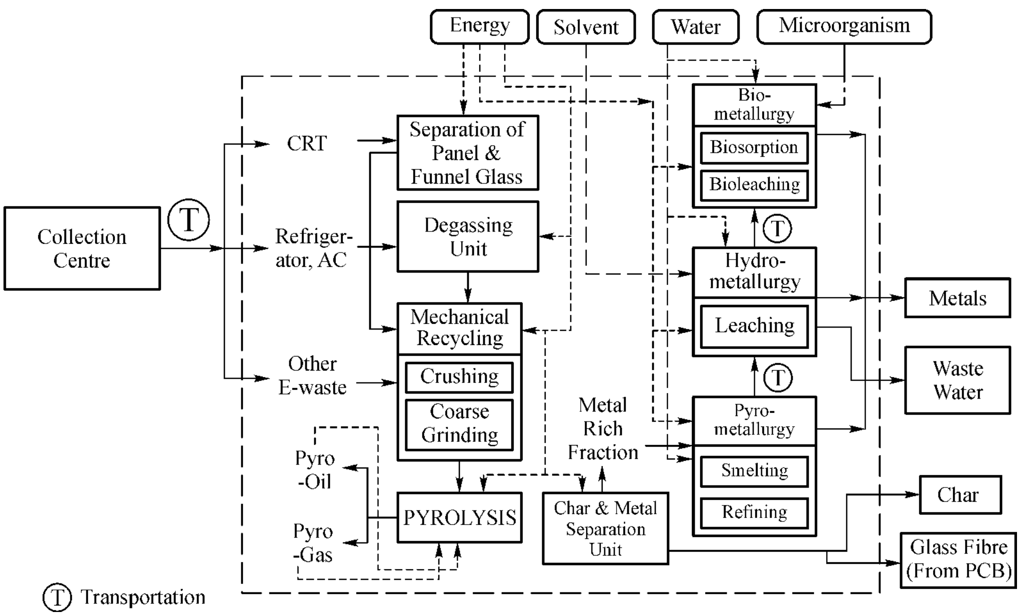

Fig. 5 Conceptual framework with light mechanical recycling and pyrolysis as pre-treatment followed by metallurgical processing for MREW (Option-2)

mechanical size reduction and a thermo-chemical process namely pyrolysis along with post separation step for isolating metal rich solids from the char residues. As per the requirement of all unit operations and chemical processes the input energy and the material resources have been clearly shown across the system boundaries. Similarly, the output streams; including metals, glass, plastic, oil, gas etc. whichever applicable have been clearly indicated. The possible emissions of carbon dioxide from different processes and unit operations incurred due to the usage of grid energy originally generated in coal or oil or natural gas based power plants as well as transportation has been indicated. LCA could not be performed due to lack of reliable data and accurate values of energy consumption, requisite material resources and so on. However, analysis of two scenarios from the principles of LCA reveals the following points.

i) Consumption of energy and in turn the depletion of fossil fuel is expected to be less in the pre-treatment process involving option 2 since it requires less severity of size reduction. As a consequence the carbon dioxide emission is also low in option 2.

ii) In option 2, pyrolysis process requires energy which can be supplied from the liquid gaseous products generated in the same process. The char resulting from pyrolysis can also be utilized for waste water treatment after activation.

iii) Hydro-metallurgical processing and electro-chemical refining is expected to have significant water footprint as both the processes generate waste water. Hydro-metallurgical processes use chemical solvents which contribute to COD of the waste water generated. As a result the possible contributions will be in the impact category of eutrophication, acidification, marine and freshwater ecotoxicity, human toxicity and water depletion. Recycling of the chemicals is a good option to reduce environmental impacts.

iv) Bio-metallurgical processes are expected to have similar impacts as different chemicals are required for preparation of the media for the culture and some waste water will be generated. But the magnitude of the impact is expected to be very less as it employs microorganism and toxic material generated during the process is limited.

v) The activated carbon used in waste water treatment may be manufactured from pyro-char.

vi) Usage of activated carbon prepared from waste biomass or any other waste materials instead of activated carbon prepared from virgin materials is encouraged. This will have some positive impact on the environment.

vii) Substantial amount of emission is associated with transportation of E-waste from collection centers to the recycling facility. It will be always preferred to have the collection centers in close vicinity of the recycling center.

viii) As found from the case studies, after mechanical recycling it is send to sister companies or third party facilities for processing and recovery of metals. This will increase the consumption of the fuel and ultimately will contribute to climate change and fossil fuel depletion.

ix) It is suggested that if the collection rate is substantially high then such processing facilities to be established in close vicinity or adjacent to the existing facility. This will reduce emissions due to transportation. However, if the rate of collection is not worthy by volume then it is better to use existing facility as new land acquisition will also have some adverse effects on the environment. Another factor, to be kept in mind that, any unit carrying out dry operations can be setup at the out skirts of any urban area as a centralized facility. If the unit to be established is for dry processing as well as metallurgical processing of E-waste, a decentralized facility will be preferred in the industrial zone. Hence, there is a trade-off between environmental aspect and social aspect.

A comprehensive presentation of LCA of individual technologies for MREW has been presented in Table 3, which reveals that the points identified by the general analysis of LCA principle is in good agreement with the reality.

5.2 Generalized discussion on economical sustainability

Economical sustainability is perhaps the most important aspect of sustainability when it comes to business. From the technological perspective, economical sustainability is there else the units would have shut down by this time. The

Table 3 Details of environmental LCA of different technologies

Technology	Type of LCA	Functional unit	Database /Method used	Geographical location	Highest impact categories
Pyrolysis (Alston and Arnold, 2011)	Comparison with landfill and incineration	E-waste containing 1 kg of plastic	Ecoinvent	United Kingdom	1. Marine aquatic toxicity 2. Freshwater aquatic toxicity 3. Carcinogens 4. Carbon Deposit 5. Climate change 6. Abiotic depletion 7. Eutrophication 8. Radiation
Pyrometallurgical processes (Ghodrat et al., 2017)	Comparison of secondary copper smelting with and without E-waste.	An input rate of 12,500 kg per hour of feed materials, (48 wt% copper scrap/metal oxides, 48 wt% waste PCB, 3.4 wt% slag and 0.6 wt% coke)	ReCiPe	Australia	1. Human Toxicity 2. Climate Change 3. Marine eutrophication 4. Freshwater eutrophication 5. Fresh water ecotoxicity 6. Water depletion
Hydrometallurgical processes (Iannicelli-Zubiani et al., 2017)	Standalone LCA	100 kg of electronic boards of mobile phones	Data obtained from pilot plant and SimaPro	EU/Italy	1. Eutrophication 2. Acidification 3. Global warming 4. Abiotic depletion 5. Human toxicity

most important thing of E-waste valorisation is metal recovery. It is nothing but chanting the '3R' mantra once again and is quite lucrative. E-waste business fostering around the world gets its maximum profit by metal reuse and recycling. Different metal recycling processes has been discussed in the section three. A summary of those processes along with their practical application in industry is presented in Table 4.

There are many economic aspects associated with the MREW units presented in Figs. 4 and 5. A generalized analysis of the two scenarios provides the following points.

(i) In option 1, mechanical recycling is rigorous and safety equipments, pollution control equipment and power consumption of the heavy machineries are few which add on extra cost of operation and maintenance, compared to option 2.

(ii) Transportation of different fractions to third party recyclers or sister companies add on extra supply chain costs but cost of setting up of new equipment and cost of land is greatly reduced.

(iii) Pyro-metallurgical processes are efficient and quite matured. These processes have evolved from their mother technologies of recovering metal from mining ores. The energy penalty of these processes is high and easily relatable to economics of the system. This is same for both option 1 and 2. However, option 2, due to pyrolysis, the load might be less.

(iv) In option 2, the resulting residue of pyrolysis contains metal, glass fiber and non-metallic char and all of these have market value. Energy input for pyrolysis is less than that of refining and smelting. The main cost associated with pyrolysis is continuous input of energy and cost of nitrogen for maintaining the inert atmosphere. Hence some cost reduction is possible at the energy input level. Additionally, the recovered materials i.e. fuels and glass fiber will generate some revenue.

(v) The hydrometallurgical processes are beneficial from an economical point of view (Cui and Zhang, 2008). These processes does not require any energy source as the energy requirement is quite low and no extra cost associated with disposal of combustion residue in landfill or in Treatment Storage and Disposal Facilities (TSDFs) (Iannicelli-Zubiani et al., 2017).

(vi) In hydrometallurgical processes, the usage of chemicals, solvent regeneration and treatment of huge amount of waste water (i.e. leaching residue) generated is a major issue and adds on extra material and operating cost. Activated charcoal required for waste water treatment, if manufactured from waste materials or waste biomass may reduce some cost. Adsorbent regeneration and spent adsorbent disposal at TSDF may incur more cost; trade-off between these two is also possible.

(vii) Bio-metallurgical processes employ bacteria, fungi or algae to recover metal and it has a business potential. Bio-metallurgy is practised in recovering metals from ores in some places. The cost of bio-metallurgy depends on price of bacteria strain, cost of chemicals required for developing the culture medium and the culture conditions. The bio-metallurgical processes are new and more research is required to understand the kinetics, thermodynamics and further studies for scale up and process intensification to turn into a sustainable technology.

5.3 Generalized discussion on social sustainability

Social sustainability of any process is complex enough to go about. The behavior, mentality and other social indicators change with geographical region. Religion also plays a big role in this case. With respect to the technologies discussed, it is quite hard to predict the social sustainability. The social LCA is the best way to understand the social impact. Social LCA study of E-waste recycling is really scant. Umair et al. (2015) have shed some light in his study on social LCA of informal sectors

Table 4 Details of metal recovery processes from E-waste

Recovery processes	Typical industry	Input material	Expected output material	Machinery involved	Disadvantages	References
Pyrolysis	Jectec, Japan	Different PCB	Cu, Fe etc	Pyrolyzer	High energy penalty	(De Marco et al., 2008; Ghosh et al. 2014)
Plasma Process	PyroGenesis Canada Inc.	All type of PCB	Base Metals and Precious metals.	Plasma torch chamber	Very costly	(Tippayawong and Khongkrapan, 2009)
CRT Treatment	E-Parisaara India	TV, Monitor etc	Hg may be recovered	Laser Cutter	Toxic pollutants and health hazard	(Ling and Poon, 2012; Ghosh et al. 2014)
Leaching	Umicore	PCB chips or paste	Gold and other precious metals	Reactor	Toxic waste water	(Hagelüken, 2006; Kim et al., 2011)
Bioleaching	N/A	PCB chips or paste at certain %	Gold and other precious metals	Bio-reactor	Very slow process	(Alan et al., 2005)
Smelting & Electro-chemical refining	Umicore, Outotec TSL, Aurubis recycling.	All kinds of PCB	Different base metals (Cu, Fe etc) & noble metals (Ag, Au, Pt).	Smelting device	Higher emission, high energy penalty, slag generation etc	(Khaliq et al., 2014; Cui and Zhang, 2008)

associated with E-waste recycling. Considering stakeholder classification (United Nations, 2007) and the study of Umair et al. the following (Table 5) sub-categories may be taken into consideration for the formal recycling of E-waste and recovery of metals.

Table 5 Stakeholder category and sub-categories for social LCA of E-waste

Stakeholder category	Subcategories	References
Worker	Working Hours	Umair et al. 2015
	Child Labour	
	Health and Safety	
	Social Security	
	Wages	
	Equal opportunities /discrimination	
Local community	Safety and health	Umair et al. 2015
	Community engagement	
	Local Employment	
Society	Public contribution to sustainable issues	Umair et al. 2015
	Contribution to economic development	
Governance	Corruption	United Nations, 2007
	Crime	
Demographics	Population	United Nations, 2007
Education	Education Level	Ghodrat et al., 2017
	Literacy	
	Awareness	

Undoubtedly, the industrial implementation of these methods will certainly create job opportunities. The society will also be benefitted with the use of recycled products fuels and the use of green technologies in the industries. Overall, with time and advancement in the technologies, more the products will be commercialized, more it will be socially accepted and we will march toward social sustainability. However, social LCA is recommended for detailed analysis.

6 Conclusions

In this study, overall sustainability of MREW technologies has been qualitatively assessed considering environmental, economic and social perspectives. Two industrial case studies have been presented to understand the state-of-the-art scenario of the recycling process of MREW technology. Two frameworks for integrated MREW units, with (option–2) and without (option–1) pyrolysis, have been conceptualized. A generalized qualitative energy and environmental impact analysis has been carried out using the principles of LCA. Due to scarcity of E-waste inventory data, the quantitative impact assessment through LCA could not be performed. Overall, option 2 has been predicted to be more efficient and sustainable compared to option 1 as it helps in reducing emissions and achieving circularity of materials through the reduction of milling energy along with generation of gaseous and liquid fuels, pyro-char and recyclable glass fibers from printed circuit boards etc. Generalized discussion from the perspective of economic and social aspects has been made. Climate change, fossil fuel depletion, water depletion, eutrophication, acidification, fresh and marine water ecotoxicity are possible impact categories that are evolved from the present analysis. The findings of the qualitative assessment of integrated MREW technology are in well alignment with previous standalone research outputs. The findings of the present assessment are expected to be beneficial to strategically decide on the research directions of MREW technologies.

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