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Valorization of waste LCD and recovery of critical raw material for circular economy: A review

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ABSTRACT

Waste an E-waste is a global environmental issue but potential resources for Indium through urban mining and recycling, which a critical raw material for the industry has been reviewed. In the e-waste, the computer followed by spent television scarp is the second highest by volume generation invariably contains the LCD panel. Indium-tin-oxide (ITO) layer in the LCD panel is an important resource for indium which has 90 wt% In_2O_3 and 10 wt% SnO_2 is a potential resource for indium has been focused in the discussion. Challenges and opportunities associated with LCD recycling and indium recovery have been critically reviewed. Indium a critical metal; scarce in primary sources but abundant in e-waste, critical in supply chain but crucial to green energy, lacking in recycling rate but progressive EOL waste generation, poses a threat to ecosystem/habitat but potential to circularize the economy, primarily as a by-product but potential urban mine, both a challenge and an opportunity, concurrently. Cost effective industrial process development is essential for a circular economy and urban mining notion, which can address the challenge associated with environment and energy and create the opportunity for circularizing the metal economy.

1. Introduction

Because of the continued strategic importance of indium as a raw material for the EU manufacturing industry, the EU Commission has classified it as a critical raw material in the first (2011), second (2014) and third (2017) list of list of critical raw materials for the EU, respectively (European-Commission, 2017). Industrial importance, application to modern technology for a better life and environment-friendly applications like clean energy application perspective place indium at the same level of PGM metal in the supply risk versus economic importance (European-Commission, 2017; http://ec.europa.eu, 2017). EU critical raw materials factsheet places indium is at substitution index for supply risk of 0.97, substitution Index for economic importance at 0.94, economic importance score 3.1 and supply risk at 2.4. Not only EU but also the US Department of Energy (DOE) (Energy, U.S.D.o., 2011) and the American physical society (APS) (Jaffe et al., 2011) has reported indium as critical for energy and emerging technology. USGS mineral commodity summaries average world production of indium during 2013–2017 was 772 tons. Fig. 1(a) represents world primary indium production on average during the year 2013–2017. The data were collected from the USGS website and averaged over the given period and averaged. The figure indicates China is the largest producer of indium constantly for several years now (38%) and the Republic of Korea follows the china in indium production (30%). Japan and Canada produced 11% of indium each, Belgium produces 3%, France produces 3.5%, Peru hardly 1.5% and Russia produces less than 1% of indium from total world production of indium (Survey, U.S.G., 2018/; Tolcin, 2015). The indium, which is an industry critical metal is obtained on the industrial scale as a by-product of zinc ores from the primary resources (Werner et al., 2015). On average, it is found in the earth crust at 50 to 200 ppb, whereas zinc ores contain 1 to 100 g/ton (Alfantazi and Moskalyk, 2003). Considering the amount of zinc ore natural resources, maximum indium obtained, as a by-product could be about 12,400 tons. While 95% of the total indium produced during zinc smelting, the remaining 5% of indium obtained from copper and tin production residues.

Ueberschaar in a 2017 report assessed the critical raw materials in WEEE and their recycling strategy. A figure adopted from Ueberschaar presented as Fig. 1(b) indicates a significant portion (55%) of indium out of worldwide production being used for ITO material (Ueberschaar, 2017). Market share for flat panel displays (FPD) (56%), solders (10%), PV cells (8%) by end use (European-Commission, 2017). EU Raw

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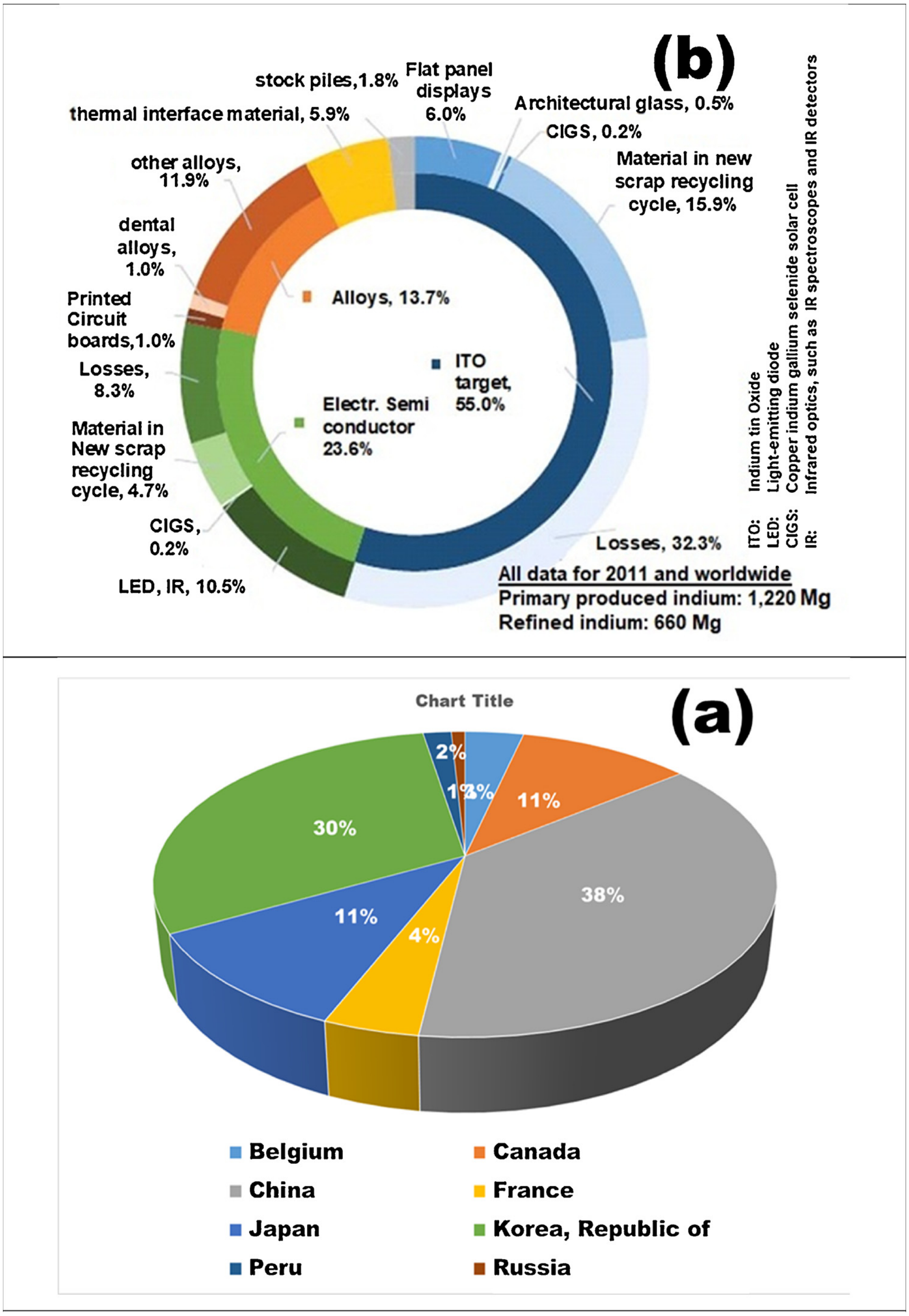

Fig. 1. (a) World primary indium production on average during the year 2013–2017, adapted from USGS webpage, (b) Market share for various products, (adapted from Ueberschaar in 2017 (Ueberschaar, 2017)).

Materials review indicated major world producer for indium are China, South Korea, and Japan produces 57%, 15%, and 10% respectively. According to two different reports indium hardly being recycled between 0–1% (European-Commission, 2017; Graedel et al., 2011a). It is estimated that indium market share of FPD may increases up to 80% of total indium production until 2025 (Goosey, 2008). FPD, which are an important consumer product mostly used as display screen products like; television, PC monitor, laptop, tablet, mobile phone. Indium tin oxide (ITO) a transparent conductive oxide material, principally used as a transparent, electrically conductive, thin-film coating for making of FPD and liquid crystal displays (LCDs) because of its favorable specific optical transparent structure and electrical conductivity (Kang et al., 2011). ITO production was the leading global use of indium (Tolcin, 2015). ITO is principally used as a transparent, electrically conductive, thin-film coating on flat-panel displays—most commonly, liquid crystal displays (LCDs). A wide range of applications of ITO as raw material and FPD as an essential component of various electronics and electrical equipment increasing the production of these products so also consumption (Choi et al., 2014). Depending upon product the FPD enters the end of life product (EOL) waste stream between 3–10 years when various electronics and electrical equipment attends its EOL. Worldwide, 55–85% of total produced indium is used in the production of ITO (Bolen, 2015). ITO mainly composed of 90% by weight of indium (III) oxide (In_2O_3) and 10% by weight of tin (IV) oxide (SnO_2) (Lin et al., 2009). The lifetime of these devices is rapidly declining due to the outdated-updated technology cycle, consumer demand for newer generation electronics product and alluring selling strategy of various producers, results in the EOL materials that enter as waste electronics and electrical equipment (WEEE) into the waste stream (Baldé et al., 2017).

BCC research has estimated the global transparent conductive coatings market to grow at a compound annual growth rate (CAGR) of 6.2% from 2016 to 2021 and market size could reach over $7.7 billion by 2021 from $5.7 billion in 2016 (Kumar, 2016). The ITO accounted for approximately 97% of the overall market for transparent conducting oxides in 2011. Indium as a raw material has extensive industrial application for a broad range of consumer electronics and electrical appliances which are used in daily life and also in modern technologies. Indium is crucial to the industrial economy around the world like the EU, Japan, China, Korea. For steady and reliable access to indium is a growing concern within the EU, Japan, Korea and across the globe as the most significant portion of indium being produced in China only. To handle the supply chain monopoly and reduce the disruptive issues in the access of indium as a raw material can be addressed through urban mining and circularizing the indium recovery and recycling. Circular metal economy and systematic waste management of these waste, recovery of metal values from these EOL waste can address the concern. Not only EOL waste but also industrial waste during the manufacturing of ITO in various processes can be a secondary resource. The EOL LCD panels and industrial waste commonly called e-waste is a richer secondary resource can be used for indium recovery. In contrast to indium content in zinc ores (1 to 100 g/ton), the EOL LCD panels with 174 g/ton (Buchert and Manhart, 2012) to 250 g/ton (Yang et al., 2013) indium are richer secondary resources than the primary zinc ore. Industrial waste like ITO itching wastewater, which contains 1.8 to 4.0 kg/ton, can even a richer secondary resource (Swain et al., 2015b).

Indium tin oxide (ITO), an important material used in displays for all kinds of everyday products such as televisions, telephones, and laptops, as well as in solar cells. Indium sources are inevitable to be consumed due to lack of alternative technology, demand for clean energy and technological significance which is amounting incremental demand of 5% yearly by 2020 (Dodbiba et al., 2012). All these reports indicate indium is at critical risk of the supply chain. The demand for indium is largely met from a by-product of zinc-lead through the hydrometallurgical or pyro-metallurgical process. Massive demand and use display mean massive EOL e-waste generation as well as waste generation during production. Lack of technology for recycling clearly provides the scope and opportunity for the circular economy. For three fundamental components like energy, environment, and economy, closing the loop for such an important critical metal is a challenge, which can be addressed through understanding the circular economy, diligent waste management, and coefficient indium recycling process development. There is no parallel perspective on the worth of e-waste, e-waste is worth of billions dollar if urban mining handled proficiently and circular economy in the action. Novelties and importance of the review are listed below.

- Currently, urban mining and circular economy are two important and significant aspects of recycling research but mostly discussed in the macro-management/policy development/policy implementation level. Whereas our current review addresses the gaps among the macro management, laboratory-based process development status and integrated industrial process development perspective.
- Based on our critical review and observation we have recommended 8 different aspects of e-waste recycling, which would provide profound insight into policy development, waste management, urban mining, and circular economy.
- After understanding the broad spectrum open literature, a schematic for feasible circular economy instead of the linear economy and the most sustainable generalized process for e-waste (e-waste in general and waste LCD in particular) recycling, which can easily be practiced and implemented has been developed.
- Indium a critical metal; scarce in primary sources but abundant in e-waste, critical in supply chain but crucial to green energy, lacking in recycling rate but progressive EOL waste generation, pose threats to ecosystem/habitat but potential to circularize the economy, primarily as a by-product but potential urban mine, identified to be a challenge and an opportunity, concurrently.
- Lack of integrated process for recovery of indium from waste LCD has been highlighted and the need for industrial feasible process development from waste LCD is recommended. The urgency for a circular economy and e-waste recycling also highlighted.

2. E-waste: generation and environmental significance

E-waste generated from WEEE is commonly divided into 3 main categories: large household appliances (refrigerators and washing machines), information technology (IT) and telecom (personal computers, monitors, and laptops), and consumer equipment (TVs, DVD players, mobile phones, mp3 players, and leisure and sporting equipment). Equipment components including batteries, circuit boards, plastic casings, cathode-ray tubes, activated glass, and lead capacitors also are considered to be e-waste (Perkins et al., 2014). A significant share of e-waste accumulated from computers, mobile phones, TVs, CRT monitors and printers (Wong et al., 2007). Relatively new technological products such as LCDs take up old products and diversify their usage areas to generate new types of electronic waste (Veit et al., 2015). The global e-waste monitor 2017 has reported 44.7 million metric tons of e-waste was generated (Baldé et al., 2017). A figure adopted from the same report shown in Fig. 2 indicated that the estimated e-waste could reach 52.2 million metric tons by 2021 (Baldé et al., 2017). Out of the total, only 20% of e-waste is recycled and the rest 80% is not documented. Among them spent television scarp is in second highest after waste computers.

Because of LCDs have many advantages besides being lighter and more compact than CRTs, over innovations the LCD has been the mainstream screen for almost all display functions. Though LCD has a less environmental impact than CRTs, but it is not free from environmental consequences. The LCD screen needs lower voltage components, no phosphorus coating, wide and miniature appearance, no geometric defects less electromagnetic radiation spread (Radha and Gurupranesh, 2014) safer disposal facilities, energy efficiency (Hischier, 2014). Of course, the LCD has disadvantages like the limited viewing angle, dead pixel defects due to the production (especially in cheaper brands) and shorter time in comparison on the average lifespan CRTs is 15–20 years. One of the components called backlight in LCDs has a short lifetime and consuming more energy from the screen (Anderson, 2005). Currently, the 1st generation CRT TVs are beyond the production and uses, but currently, the 2nd generation FPDs are mainly consumed and produced because of better functionality, excellent optoelectronic properties, and proficient design (Swain et al., 2018, 2016a). Nowadays LCD is an integral part of in all type of electronic device such as TV units, laptops, monitors, mobile phones, equipment displays and billboards as a screen. FPD also now part of electric appliances because of the inclusion of smart technology into electric appliances. All these consumer electronics products have an average lifespan of 3–5 years (Zhuang et al., 2012) and electrical appliances have an average lifespan is about 10 years. Fig. 3 adapted from the global e-waste monitor 2017 (Baldé et al., 2017) shows discarding probability versus product lifespan of electrical and electronics equipment indicate and the same lifespan as reported by Zhuang et al. (Zhuang et al., 2012). It is estimated that 25 million m^2 of waste LCD panel will be entered Europe's waste recycling in 2015 [78]. Hence, most of the e-waste like EOL television scarp, EOL television scarp, and EOL television scarp contains ITO in the FPDs. FPD otherwise called LCD, panels are manufactured in several different technological variants, can be classified as 3 different types such as

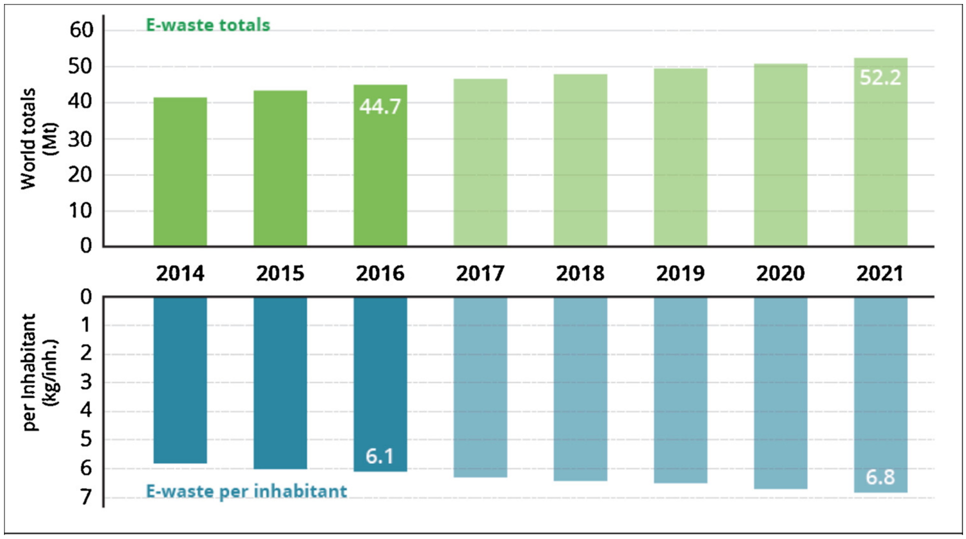

Fig. 2. Estimated e-waste production in million metric tons by 2021. From 2014–2016 data collected, 2017–2021 estimated, (adapted from Baldé et al. (Baldé et al., 2017)).

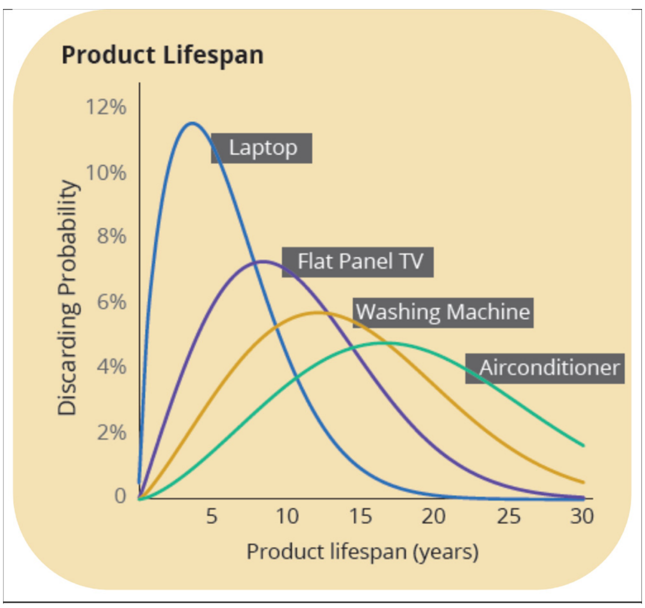

Fig. 3. Discarding probability versus product lifespan of electrical and electronics equipment (adapted from the global e-waste monitor 2017 (Baldé et al., 2017)).

twisted nematic (TN), vertical alignment (VA) and in-plane switching (IPS). TN Panels are the most commonly used inexpensive devices has a fast response time, VA Panels offer better color and wide viewing angles have a higher response time and lower response speed than TN Panels. IPS technology has a satisfactory response speed while offering the best quality color and visibility but these are most expensive among all three FPDs. Fig. 4(a) shows a common schematic for the FPD or LCD and general structure and Fig. 4(b) shows the basic construction of an electro-optic LCD device (side view). Fig. 4(b) clearly indicated two layers of ITO thin film being used in LCD glasses, which is an indium-rich component and lucrative resources for indium through urban mining. LCD technology was being used commercially from the middle of the 1980s and containing high-quality glass in the LCD panels used between 1987 and 2013 was able to cover an area of 2230 km^2 (Pérez, 2014). LCD panels are used in laptops, monitors and TV units respectively according to the size of the used areas. The most widely used areas from the first days of LCD panels becoming widespread are shown in Fig. 5. Fig. 5 shows the use of FPDs in square feet year by year from 97 to 2012 in the various products like TV, PC, notebook and smaller electronics applications. Fig. 5 clearly shows the amount of FPDs used for TV is the highest and monitor follows the 2nd highest and mobile PCs follow the next. Area of FPD uses, EOL waste displays clearly shows the volume is huge.

E-waste also contains not only precious and/or critical metals of significant economic value and strategic important metal from growing global resource scarcity perspective but also hazardous substances such as aluminum, barium, beryllium, cadmium, chromium(hexavalent), copper, lead, mercury, molybdenum, nickel, tin, and zinc (Perkins et al., 2014). Disposal e-waste without treatment can be a potential health hazard either to human, animal, and ecosystem. The hazardous and fatal aspect of exposure of cadmium, chromium, lead, and mercury is well known and virtually affect all organ systems including cardiovascular, nervous, renal, gastro-intestinal, and respiratory systems (Tchounwou et al., 2012). Toxic effect of aluminum is neurotoxic, able to cause a brain disorder (encephalopathy) (Yokel, 2014). Copper causes Wilson's Disease, characterized by hepatic cirrhosis, brain damage, demyelization, renal disease, and copper deposition in the cornea (Barceloux and Barceloux, 1999a). Indium also a potential health hazards can damage the lungs, liver, kidney and even can damage developing foetus (Yang, 2015). Molybdenum does have physiological effects and most apparent in the bones, liver, and kidneys (Barceloux and Barceloux, 1999b; Gupta and Gupta, 1998). Sn is associated with depressions, liver damage, malfunctioning of immune systems, chromosomal damage, shortage of red blood cells and brain damage (causing anger, sleep disorders, forgetfulness, and headaches) (Lenntech, 2014).

Association of e-waste pollution with thyroid malfunction, changes in cellular expression and function, changes in temperament and behavior, decreased lung function and adverse neonatal outcomes have been reported by Grant et al. (Grant et al., 2013). Evidence of greater human DNA damage because e-waste exposure has also been observed by Grant et al. (Grant et al., 2013) Their findings also include increases in spontaneous abortions, stillbirths, and premature births, and reduced birthweights and birth lengths associated with exposure to e-waste (Survey, U.S.G., 2018/). Similarly, Noel-Brune at al. indicated genotoxicity, abnormal thyroid function, and thyroid development, neurobehavioural disorder, congenital malformations like health consequence because of exposure to e-waste (Noel-Brune et al., 2013). Risk of fetal loss, prematurity, low birthweight consequence because of exposure to e-waste also reported (Noel-Brune et al., 2013). Cancer risks

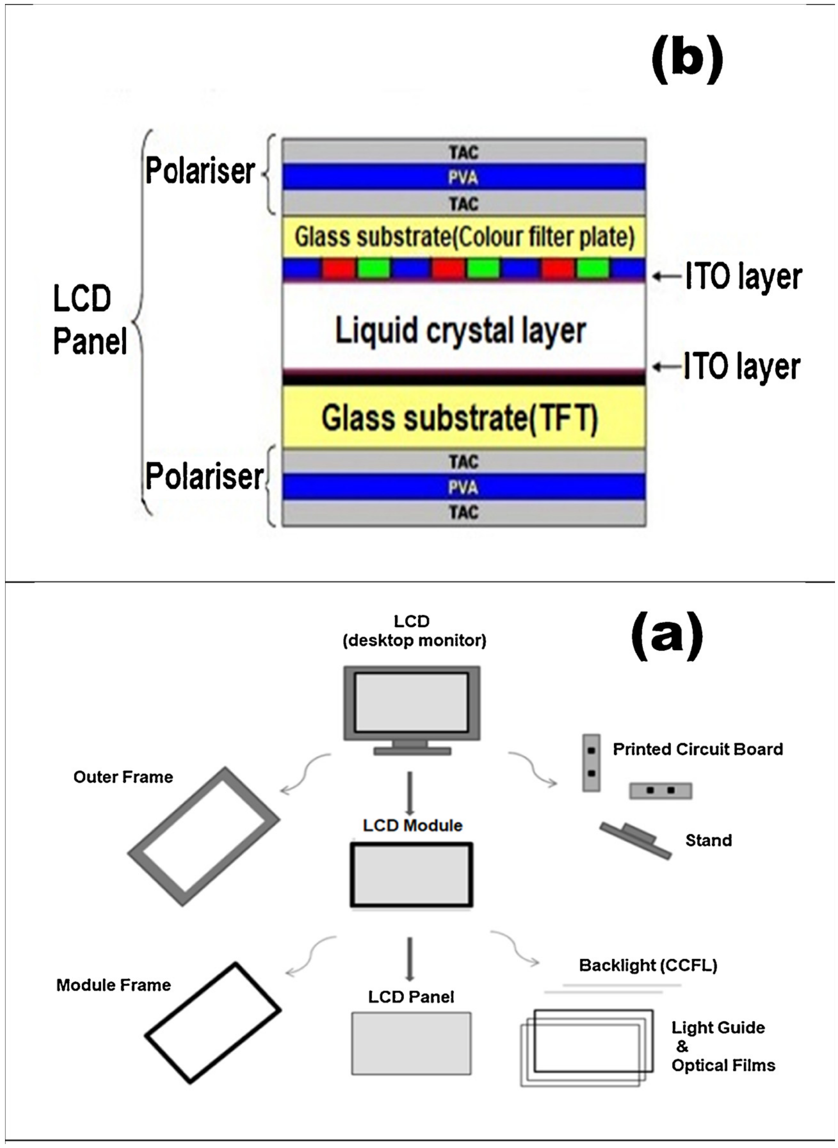

Fig. 4. (a) The major component in LCD and its general structure, (adapted from, (Yang 2012 [78]), (b) Basic construction of an electro-optic LCD device (side view), (adapted from Dodson et al., 2012 [44]).

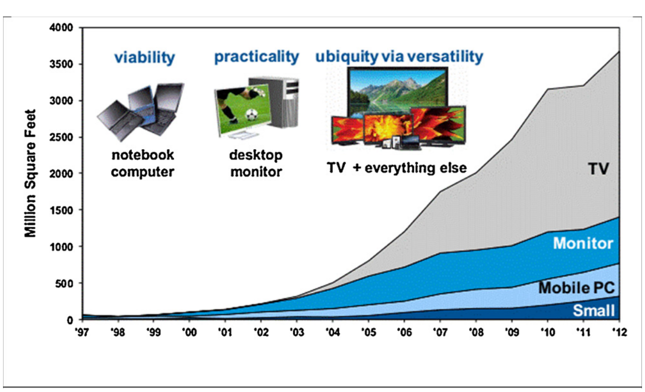

Fig. 5. The LCD glass demand developed through three successive waves of application growth, (adapted from Perez, 2014 [31]).

for humans from exposure to the semiconductor metals have been reported by Fowler et al. (Fowler et al., 1993). Children and neonates are the most vulnerable groups to e-waste exposure should be a greater concern (Song and Li, 2015). Chen et al. assessed e-waste toxicity and concluded that e-waste poses a significant threat to ecosystems and public health due to excess toxic metals (Chen et al., 2018). The World Health Organization (WHO) has raised concern over growing global e-waste problem and it's harmful to effect on vulnerable populations, and safer recycling of e-waste has been recommended and pledged (Heacock et al., 2016; Perkins et al., 2014). Chonan et al. and Nogami et al. have reported interstitial pulmonary disorders is associated with ITO waste (Chonan et al., 2007; Nogami et al., 2008). Recent severe restrictions imposed on the use of mercury in manufactured products also give motivation to the promotion of recycling LCDs because of mercury (UNEP, 2017).

Not for the environmental challenges but also from supply chain scarcity, depletion of natural resources, keeping the competitive edge of industries for critical raw material, to get rid of the monopoly of certain countries the e-waste is a potential resource and circularize the economy could the only answer to the crisis. As e-waste management, resources recovery from e-waste, circularize the e-waste economy and e-waste urban mining is the complicated environment, social and economic issues. Reviewing the total e-waste recycling may distract the concentration. From a technology development perspective also the e-waste is an extremely complicated issue needs to be addressed edge by

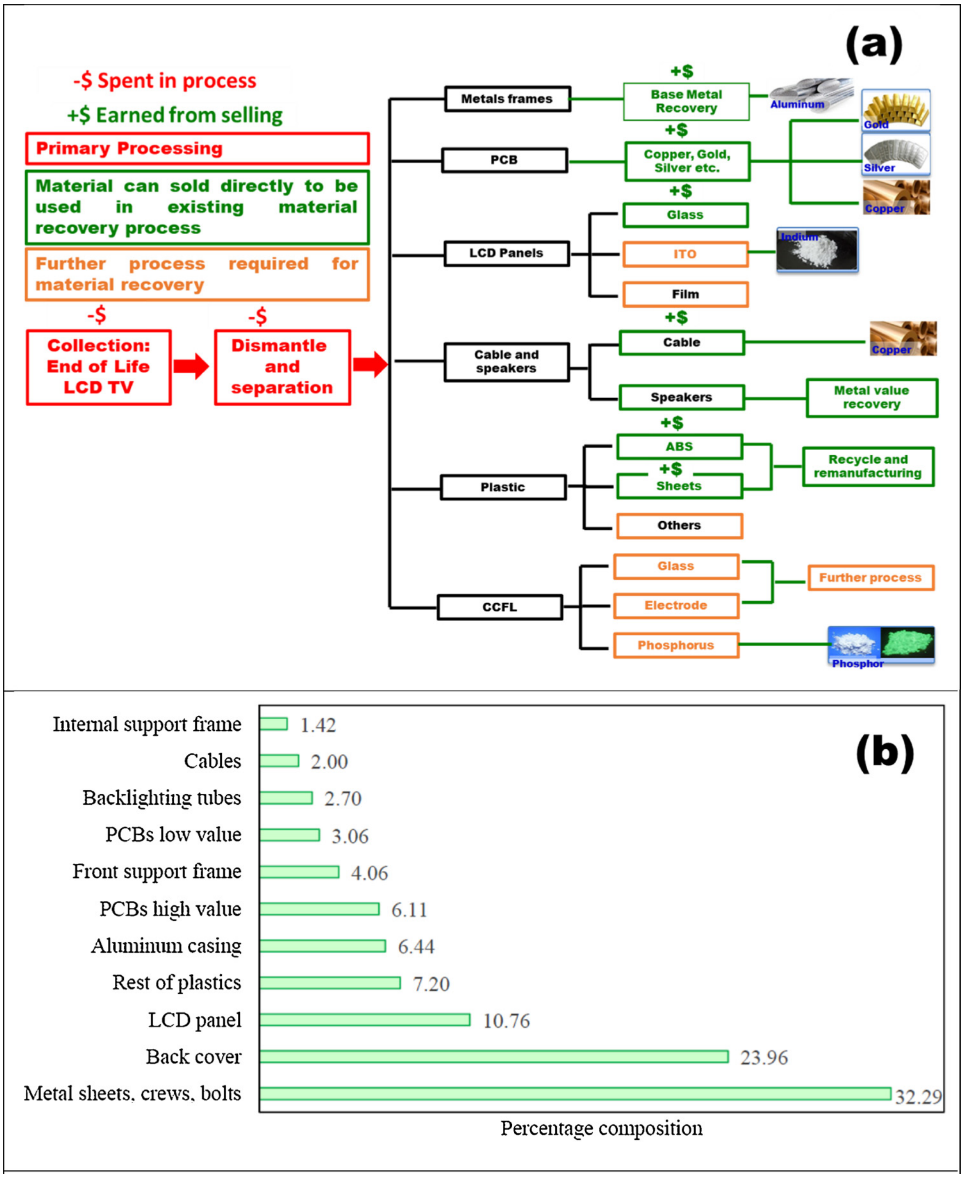

Fig. 6. (a) Flow diagram for qualitative cost-revenue analysis of waste LCD(adapted from (Swain et al., 2016a), and modified), and (b) % of the various component present for material recovery/revenue generation.

edge. Hence, the current review focuses on recovery indium a critical raw material and its recovery from e-waste in general and from waste LCD/FPD components in particular. Although Zhang et al. have reviewed recycling indium from waste LCDs mainly focused on the highly developed single recycling and reusing techniques (Zhang et al., 2015).

3. E-waste valorization and its circular economy

Though several reports regarding the dismantling of waste LCD and metal values mainly indium recovery from ITO bearing component of the LCD screen has been published, but the cost-effectiveness of the process rarely been reported. Fig. 6(a) represents process flowsheet for values recovery from waste LCD and indicated a qualitative spending-earing process for recirculating resources from waste LCD. The flow sheet represented in the figure has been adapted from the reported process (Swain et al., 2016a) on dismantling, beneficiation and total recovery process of waste LCD TV. Recently D'Adamo et al. have reported a techno-economic analysis on waste LCDs as a source and % each component present in the waste LCD (D'Adamo et al., 2019). Fig. 6(b) represents % recoverable material component in the waste LCD adapted from (D'Adamo et al., 2019). D'Adamo et al. (2019) have analyzed the profitability of LCDs recycling processes by discounted cash flow (DCF) analysis. Cost and revenue of a typical 2000 tons/year recycling plant using hydrometallurgical technologies for metal recovery was investigated. Input data for cost involve and revenue generation was analyzed for USA, Europe, and China. Profitability was analyzed based on input cost and recycled material cost which represented in Fig. 6(b) above. The analysis concluded that though profitability depends upon several factors, but when there is disposal fee involved, the industrial circular economy of waste LCD recycling is profitable otherwise a marginal loss was involved. Kang et al. have investigated the economic of e-waste recycling in California and also concluded that a fee-based recycling process can be quite profitable (Kang and Schoenung, 2006). Andarani et al. have analyzed small scale economic feasibility of e-waste treating facility in Sarang, Indonesia and indicated that by the manual dismantling of e-waste (due to lower labor cost) business unit can make a profit (Andarani and Goto, 2012). An united nations industrial development organization (UNIDO) report on the economic feasibility of e-waste treatment in Tanzania indicated e-waste recycling can be profitable because of its intrinsic values

(Fabian Blaser, 2012). Mostafa et al. have studied the economic feasibility of e-waste recycling in Egypt and indicated sound profitability for e-waste circular economy (Mostafa and Sarhan, 2018). Based on the above review, we strongly believe that even without disposal fee assistance, the circular economy for waste LCD definitely be profitable and futuristic because of the following cause.

(i) Carbon economy or carbon emission related tax or futuristic carbon emission tax.
(ii) Automation or semi automation can reduce process cost in developed nation.
(iii) Volume processing and extended capacity utilization can increase profitability.
(iv) Resources deficient country like Korea and Japan, a developing nation where labor input is minimal and countries where energy input is cheaper, definitely would be cost effective.
(v) Metal price is ever growing; hence future could be bright though dependent on the economy.

4. Waste LCD a lucrative E-waste and urban resource for indium

EU Commission has recently reviewed the critical raw materials and extended the list of critical materials (2017) to 27 in the third list of critical materials from 20 critical materials in the second list (2014), which was only 14 in the first (2011) (http://ec.europa.eu, 2017). Most importantly, the indium has been listed in all three lists. Similarly, the growing role of minerals and metals for a low carbon future published by the ınternational bank for reconstruction and development/the world bank in June 2017 considered indium as rare earth metal. Rather the indium is also clean energy and low carbon critical metal. The report indicated global cumulative demand of indium for CIGS solar PV technology could reach 50,000 tons through 2050 in a conservative estimation. Which could be 50% deficit considering the current rate of indium production (Arrobas et al., 2017). Wang et al. have reported in the period between 2013–2035, the demand of the indium could be much higher than the recovery rate of end-of-life LCD panels technologies (Wang et al., 2015). Wang et al. also suggested for the need for improving existing indium recovery technologies (Wang et al., 2015). Considering supply-demand disparity, global competitiveness, indium supply security, stable price and to keep cope with technologically advanced lifestyle, the circular economy should be the resolution. For the circular economy of indium, sustainable recycling and recovery from e-waste should be a panacea. An economically feasible, eco-efficient and sustainably effective recycling/recovery of indium from the display screen in general and from LCD, in particular, is sustainable from the circular economy, low carbon, clean energy, and environment-friendly perspective. In an ideal situation, if quantitative LCD recycling can be achieved with respect to indium, hence, the supply-demand disparity can be addressed absolutely (Dodson et al., 2012).

Dodbiba et al. have suggested that LCD panels can also be used as an important alternative for critical metal like indium source (Dodbiba et al., 2012). Boundy et al. have reviewed the comparative indium content in the various waste LCD panel and their respective analytical technique used to determine the content have been summarized in Table 1 (Adapted from Boundy et al., 2017 (Boundy et al., 2017)). The table clearly indicates the indium content in the waste LCDs varies from 100 g/ton to 400 g/ton, which is richer than primary resources like zinc ores for indium where indium content in zinc ores varies 1 g/ton to 100 g/ton. Table 1 without ambiguity reflects that waste LCDs are a far better resource than primary resources. On the other hand, the global rate of indium recovery is in between 0 ≤ 1% from EOL products or e-waste (Graedel et al., 2011b), which provides both challenges and opportunity. Waste LCD is a lucrative urban resource for indium needs effective beneficiation strategy and recovery process. Currently cost for ITO bearing LCD is absolutely nothing other than transport. Indium recovery from the EOL LCD associated with the same challenges like collection (depending upon country), dismantling and recovery of indium.

Table 1
Comparison of published average indium contents in waste LCD screen/glass. NS: not specified (Adapted from Boundy et al. (Boundy et al., 2017)).

Method	Indium Content (g/ton)	Mass Basis	Reference
Leach/ICP-MS	130	Glass	(Rocchetti et al., 2015a)
Leach/ICP-OES	300	Glass	(Ruan et al., 2012)
Leach/ICP-OES	1000	NS	(Dodbiba et al., 2012)
Leach/ICP-OES	200 ± 50	Screen	(Yang et al., 2013)
Leach/ICP-OES	380–410	Glass	(Hasegawa et al., 2013a)
Leach/AAS	175 ± 60	NS	(Susanne et al., 2013)
TCLP test	102	Glass	(Wang, 2009)
NS	260.7	NS	(Lee et al., 2013)
XRF	164	Screen	(Boundy et al., 2017)

Waste LCD screen bearing EOL TV, PC, laptop, mobile phone, and other electronic devices has complex configuration depending upon manufacturer needed proper dismantling. When dismantled, all the parts are possible to recover separately. Once dismantled, the LCD panel itself has a non-homogeneous complex structure in terms of the materials and compositions. The LCD panel itself has a non-homogeneous complex structure in terms of the materials and compositions they contain. The whole LCD panel contains parts such as LCD, plastic cover, backlight unit, power supply unit, control unit, rear frame and stands foot. Swain et al. have discussed beneficiation and recovery of indium from LCD glass, where the strategy for indium recovery mainly follows dismantling and separating various units followed by recovery of indium (Swain et al., 2016a). Dismantling and separation of LCD panel units is the important process required for recovery of indium from ITO in LCDs has been reviewed below.

5. Dismantling of LCD to access the ITO film

In the first stage of the recovery phase, separating the LCD unit from hazardous backlight lights and potentially valuable parts like circuit boards, cables, metallic and plastic materials through a suitable dismantling process (Fontana et al., 2015). Fig. 7 shows various units after dismantling of the LCD display device and schematics for the LCD panel (Ma and Xu, 2013). It mainly consists of the backlight unit, glasses, plastic, PCBs, metals frames, and connecting wires. Fisher et al. and Li et al. have reported that a typical LCD display device provides 40–50 weight % of a glass material, 35–40 weight % backlighting and its modules and rest are PCBs and wire (Fisher et al., 2004; Li et al., 2009). Currently, worldwide waste LCDs are manually dismantled and value added through the separation of different units in both formal and informal recycling sector (Ferella et al., 2017). Fig. 8 shows dismantling followed by separation manually essentially by an electrical screwdriver. The dismantling and separation of each unit follow the sequences as; dismantling of LCD base unit, back cover, cables, PCBs, metal panels and separation of LCD unit. Followed by, from LCD unit electrical wires and PCBs are separated. Finally, the backlight unit needs to be separated with maximum care possible to avoid occupational hazard from mercury. Followed by dismantling and separation of units, the ITO bearing LCD panel can be obtained which contain the critical metal indium need to be recover for circular economy (Zhuang et al., 2012). Though several researchers report has been published on indium recovery from waste ITO film of LCD panel, but the rate of indium recycling is only < 1% (Graedel et al., 2011a). Prime contributing factor mainly lacks of commercial technology from indium recovery from waste ITO (Swain and Lee, 2019). As the rate of Indium recycling is significantly poor (< 1%), and commercial indium recovery process from LCD waste in particular and e-waste in general is hardly exists, eco-efficient commercial process needed to be developed. After the ITO, the backlight unit in the LCD panel, which is equipped with cold

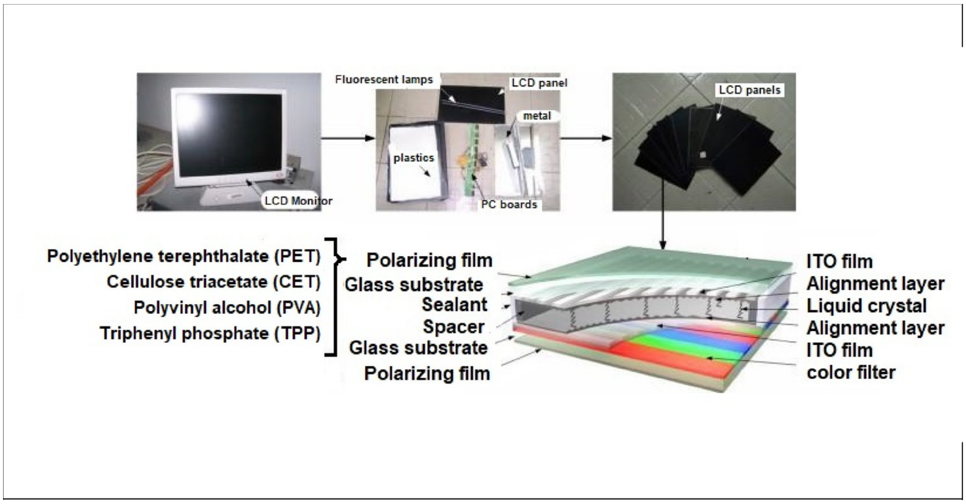

Fig. 7. Schematic diagram of a dismantled waste LCD panel (adapted from Ma and Xu, 2013 (Ma and Xu, 2013)).

cathode fluorescent lamps (CCFLs), containing significant amount of mercury need special attention and process. Isolation of backlight unit is quite essential. The isolated mercury and wastes from isolation should be treated with hazardous waste management facilities. Recent Minamata convention on mercury by UNEP severe the restrictions imposed on the use of mercury also give motivation to the promotion of recycling LCDs because of mercury and limiting manual dismantling of LCD from an occupational hazard perspective (UNEP, 2017). Hence, performing automatic dismantling process in a closed system is important to prevent mercury release in terms of environmental health. Otherwise, the separated material is classified as hazardous waste due to its mercury content and becomes unsuitable for subsequent recovery/recycling processes (Wrap, 2011). Because lack of technology for indium recovery and mercury isolation, the glass material obtained from the separation process is not currently recycled at an industrial scale. These waste in particular either landfilled or subjected to incineration. Thus, loss of such a critical metal like indium paralyzing the circular economy and encouraging the depletion of primary resources, which provide an opportunity for Indium recovery from e-waste (Fontana et al., 2015).

Although indium recovery from several waste/secondary resources, i.e., ITO-scrap (Hsieh et al., 2009; Li et al., 2011b; Virolainen et al., 2011), EOL LCDs (Hasegawa et al., 2013a) and etching waste (Kang et al., 2011; Liu et al., 2009) have been studied but most of the reports

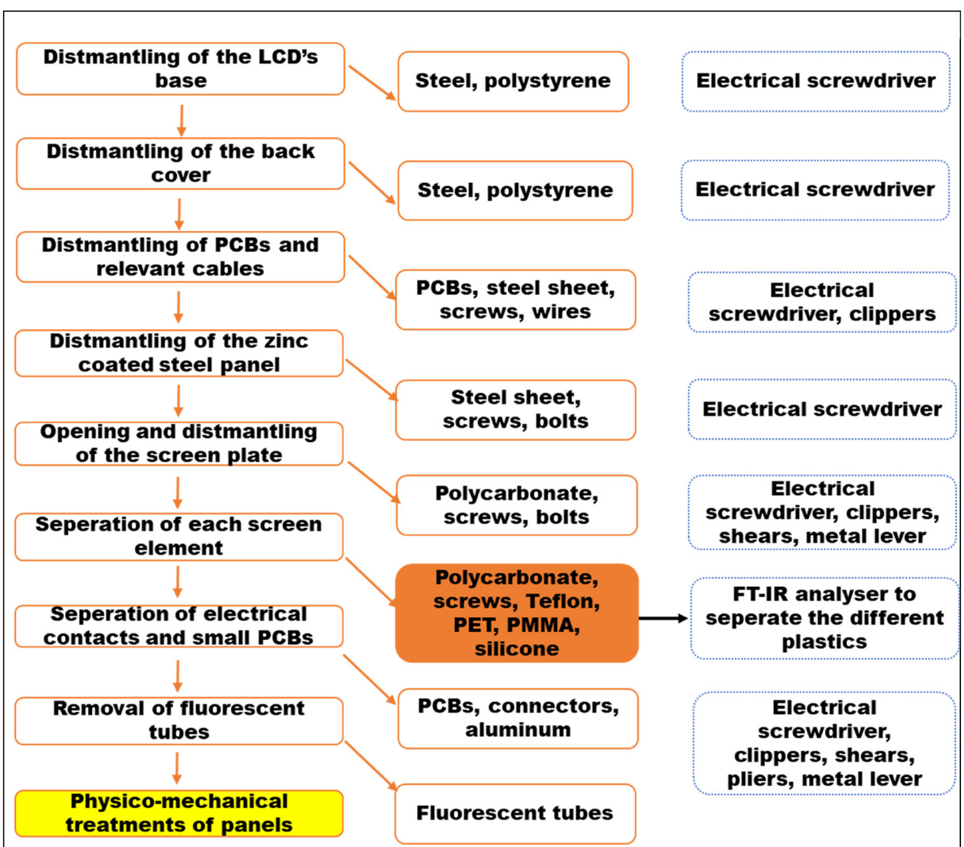

Fig. 8. Flowsheet for the manual dismantling of LCDs (adapted from Ferella et al., 2017 (Ferella et al., 2017)).

are related to only laboratory scale of investigation, which indicates a long way to go for techno-economical eco-efficient industrial recovery of indium from secondary resources like ITO bearing LCD waste. Indium recovery not only from e-waste but also various industries like semiconductor industry or electronic device manufacturing industry waste have been investigated and reported in the literature

Hong et. al reported recycling of the In from ITO-sputtering waste mostly deals with enrichment of indium-containing waste powder from the sputtering chamber wall (Hong et al., 2010). Kang et al. reported the recovery of indium from etching waste by solvent extraction and electrolytic refining, but they have used a solid cake from ITO etching industry (Kang et al., 2011). Liu et al. studied the recovery of indium from etching wastewater using supercritical carbon dioxide extraction (Liu et al., 2009). Virolainen et al. investigated the recovery of indium from ITO, but mainly used commercial ITO sample for leaching followed by solvent extraction (Virolainen et al., 2011). Gu et al. also investigated very similar target for indium tin separation (Gu et al., 2017). Most of the research reported is focused on the recovery of indium from these waste resources and are mainly investigated in laboratory scale only. In the open literature, various recovery processes for indium recovery has been reported, which can be mainly classified as (i) Hydrometallurgical processes (Chemical treatment), (ii) Pyrometallurgical process (Thermal treatment) and (iii) Bio-hydrometallurgical process (Biological treatment). Each of the reported processes has been further reviewed in the separate section below.

6. Indium recovery by pyrometallurgical process from waste LCD

The pyrometallurgical process being applied for the recovery of metal values and recycling of e-waste and industrial wastes. Several authors have reported the pyrometallurgical process for recovery of indium from various secondary resources like e-waste and industrial wastes (He et al., 2014; Itoh and Maruyama, 2011). Usually, these processes are multistage processes and of course energy intensive and carbon inefficient process. Ito et al. proposed a pyrometallurgical method for indium recovery from ITO scrap which is a two-stage process (Itoh and Maruyama, 2011). Fig. 9 shows a pyro-metallurgical process for the recoveries of metallic indium and tin from ITO scrap developed by Itoh et al. (Itoh and Maruyama, 2011). In the first stage, the ITO scrap is alloyed as indium-tin alloy at relatively low temperature by CO reduction, in the second stage, indium metal was vaporized by taking advantage of indium and tin vapor pressure difference. The vaporized indium was cooled down and collected as metallic indium. Finally, metallic tin residue remained in the furnace, which can be collected. An important drawback of the process is, the reported process is a high-temperature process and processed at 1373 K temperature. Considering ITO bearing glass in waste LCD, the reported process hardly can be suitable. Similarly, He et al. has reported recycled indium from waste LCD by vacuum carbon-reduction. He et al. studied vacuum carbon-reduction process from In_2O_3 and applied their finding to waste LCD powder. Efficient recovery of indium like 90% was achieved using

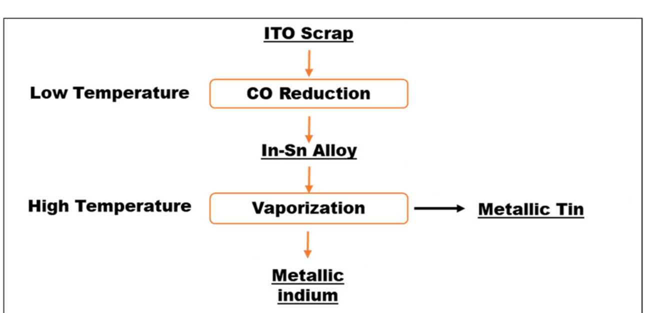

Fig. 9. Shows a pyro-metallurgical process for the recoveries of metallic indium and tin from ITO scrap, (developed by Itoh et al. (Itoh and Maruyama, 2011)).

the optimized parameters such as 1223 K and 1 Pa with 30 wt% carbon addition for 30 min (He et al., 2014). Takahashi et al. have reported indium recovery from LCD of the discarded phone by chloride induced vaporization process (Takahashi et al., 2009). The reported process is quite similar to the reported process reported by Ito et al., with an exception that the waste ITO bearing sample was with hydrochloric acid (HCl) solution prior to vaporization process. The ITO bearing sample was first treated with an aqueous HCl solution to alter the structure of the In_2O_3 compound in the ITO. Then indium was vaporized follwed by condensed to recover indium (Takahashi et al., 2009). Significant drawbacks of pyrometallurgical technique for indium recovery are (i) highly energy intensive, (ii) adverse carbon economy which limiting cleaner production technology (iii) needs expensive industrial machinery, (iv) mostly operated in large scale involve large scale investment, and (v) produces toxic gasses subject to environmental regulations rarely attract industrial interest for recycling. All these factors negate the circular economy because environment, energy and economy concern whereas hydrometallurgy can successfully handle the challenge as small-scale hydrometallurgy plant can handle the disadvantages of the pyro-metallurgy process.

7. Indium recovery by bio-hydrometallurgical process from waste LCD

Due to the environment-friendly and coefficient process, the bio-hydrometallurgical process has gained considerable importance in recent years for waste treatment and metal recovery. Bioleaching which derived from bio-hydrometallurgy is the rudimentary stage for metal value recovery, in which the target metals are recovered from the solid materials in an economically efficient manner with eco-friendly processes (Wang et al., 2015). In the bioleaching process mainly metals are leached using acidophilic microorganisms in an appropriately acidic environment. Since the bioleaching is a biocompatible process, no need to mention that, it is environment-friendly though traditionally believed to be a complex process to understand the leaching mechanism. The complex bioleaching mechanism of metals is now being well known, and it is being economically applied to the recovery of metals from various mineral resources (Pradhan et al., 2010; Sand et al., 2001). Several researchers have advocated that a large number of bacteria have the ability to leach metals (Ilyas et al., 2013; Panda et al., 2015) which is very similar to commonly practiced acidic-alkali leaching in hydrometallurgy process. As an alternative to hydrometallurgical and chemical metallurgy process, bioleaching can be used for recovery of metal values from primary low-grade ores or from secondary industrial wastes (Kim et al., 2010; Pradhan et al., 2017) even e-waste. Bioleaching using acidophilic microorganisms like; *Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans* and *Leptospirillum ferrooxidans* has been used by several researchers for metal leaching from sulfide-based minerals (chalcopyrite, pyrite) (Pradhan et al., 2017).

The bioleaching process has been applied for leaching of zinc-bearing ores and studied well. have been studied. Hence, the bioleaching can well be efficiently applied since indium is commonly occurred with zinc and produced as a by-product of zinc. Martin et al. have investigated the bioleaching of sphalerite ores (containing 400 g/ton indium) which yield 85.4% leaching in shake flask reactor and the same was 79.9% in glass column reactor (Martin et al., 2015). For the indium leaching purpose iron oxidized and sulfur oxidized species microorganism was used for bioleaching. Wang et al. have reported bioleaching of Pb-Zn slags which were leached in the autotrophic medium. Wang et al. have reported that the iron yield was 71% in the case of iron oxidized -sulfur oxidized and mixed culture (Wang et al., 2015). Jowkar et al. have investigated indium bioleaching from spent LCD screen adapted Acidithiobacillus thiooxidans type acidophilic microorganism for the bioleaching (Jowkar et al., 2018). Fig. 10 depicted the process adapted by Jowkar et al. for indium recovery from the waste LCD

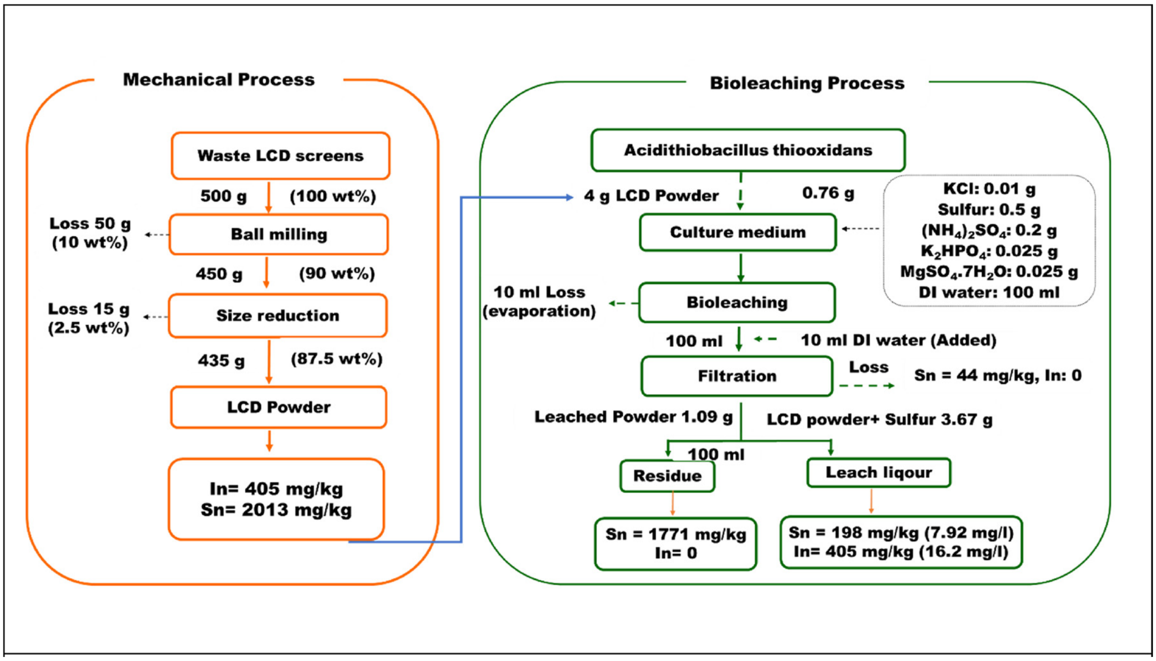

Fig. 10. Indium recovery from spent LCD screen by the biohydrometallurgy. The mass balance flow-sheet of the overall process (developed by Jowkar et al. (Jowkar et al., 2018)).

screen by the biohydrometallurgy process (Jowkar et al., 2018). As reported by Jowkar et al., waste LCD cullet was ball milled for further size reduction which is suitable for efficient bioleaching. From the ball milled LCD powder, indium leaching process was optimized and in the optimum condition, quantitative indium was bioleached using Acidithiobacillus thiooxidans. The optimized bioleaching condition was such; pH was 2.6, solid to liquid ratio (weight of waste versus volume culture medium) was 1.6 w/v and concentration of sulfur was 8.6 g/L (Jowkar et al., 2018). Jowkar et al. clearly indicated bioleaching of indium from waste LCD can be an alternative environment-friendly option for the indium recovery. Since bioleaching is only a metal extraction process, the extracted metal bearing leach liquor needs further processing for metal purification and recovery. Similar to conventional hydrometallurgy process, from the biol-leached leach-liquor indium can be recovered directly by selective cementation or selective precipitation. Considering intrinsic drawback of precipitation processes like purity and slow kinetics, the indium can further be purified by solvent extraction or ion-exchange process. Otherwise, from leach liquor, the indium can be further purified by solvent extraction followed by recovery as reported process elsewhere (Swain et al., 2015a, b).

8. Indium recovery by hydrometallurgical processes from waste LCD

Hydrometallurgical processes are versatile and flexible, offer scope for innovation and redesign process flow sheet for efficient metal recovery. Unlike the pyro-metallurgical process, the hydrometallurgy process produces no to negligible toxic gas, do not require a high-temperature process, and expensive instrumentation. Hydrometallurgy process can be operated in small scale and medium scale. Other process advantages, several technical positive aspects such as easier control of chemical reactions, lower density and non-specific process parameters, lower cost, flexibility, and less emission release make these methods more suitable for industrial-scale production of metals. The hydrometallurgy process not only used for metal recovery from primary resources or ores processing but also used for metal recovery from secondary resources, wastes recycling/e-waste recycling/LCD waste recycling (Pradhan et al., 2017; Zhang and Xu, 2016). In general metal recovery by hydrometallurgy includes three fundamental sequence, like leaching (acid, mix-acid, alkali, organic acid leaching, etc.) for extrication of metals, separation/purification (ion exchange, solvent extraction, membrane, adsorption, etc.) of selective metals and finally pure metal recovery (electro-winning, precipitation, cementation, reduction). Numerous author, in general, has used the hydrometallurgy technique for valorization e-waste (Ashiq et al., 2019; Debnath et al., 2018; Kamberović et al., 2018), recovery of precious metal from e-waste (Amil Memon, 2016; Canda et al., 2016; Quinet et al., 2005) and recovery of critical metals (Sethurajan et al., 2019; Sun et al., 2017; Yang et al., 2017). Also, several authors have reported indium recovery in particular by the hydrometallurgical process (Swain et al., 2018; Swain and Lee, 2019; Swain et al., 2015a, b) from the e-waste.

Indium extraction by mineral acid leaching or alkali leaching from waste LCD has been extensively studied and reported in the literature. Zhang et al. have reported quantitative leaching indium of LCD using 0.8 M HCl as lixiviant and 300 W ultrasonic waves for 60 min from uncrushed LCD cullet (Zhang et al., 2017). The same group also investigated indium leaching from LCD using H_2SO_4 and assisted by ultrasound. As reported, a significant 74.1% of indium leaching was achieved at the industrial feasible conditions i.e., ultrasound power of 800 W, a reaction temperature of 60-70°C, the sulfuric acid concentration of 0.5 mol/L, particle size smaller than 0.5 mm (Zhuang et al., 2016). Comparison indium leaching result by cullet size reduction and un-crushed LCD cullet indicated cullet size reduction can provide efficient leaching, but both the comparison subject to investigation to understand which should be the better for industrial scale mass production. Zeng et al. also investigated indium leaching from LCD using H_2SO_4, and optimal condition reported as $< 75\,\mu m$ sample size, 180 min retention time, 50 °C temperature, H_2SO_4 for the leaching agent, 100 g/L initial concentration, and 1:1 liquid-solid ratio (Zeng et al., 2015). Laura et al. have suggested considering indium content in EOL LCDs (˜100 ppm), a single step of leaching is not cost-effective, hence, multistage leaching using 2 M H_2SO_4 at 80 °C for 10 min could cost-effective (Rocchetti et al., 2015b). Leaching is usually carried out in an acidic medium with a single type of acid or a mixture of different acids (Fontana et al., 2015). Taking into account the leaching is the rudimentary stage for indium recovery from LCD by hydrometallurgy, the above summary clearly indicates that mainly indium can be leached from LCD through acidic leaching using either HCl or H_2SO_4. For efficient leaching and make cost-effective other parameters like; concentration of acids, temperature, college size reduction, ultrasound assistant and countercurrent leaching play important role needed to be considered in industrial scale optimization. During literature investigation we have realized that through HNO_3 and aqua regia also used for indium leaching, considering environmental adversity those are should not be used in industrial scale. The same also industrially not preferable because of extreme corrosive behavior. Alkali leaching of LCD waste for indium recovery quite uncommon, but Park has reported the recovery of indium from ITO target scrap by alkaline hydrothermal reaction through the conversion of In_2O_3 to $In(OH)_3$ (Park, 2011). Swain et al. reported acidic leaching process for waste LCD and optimized indium leaching using concentrated hydrochloric acid(Swain et al., 2018, 2016a). Possible leaching parameters such as; effect of acid concentration, solid-liquid ratio, temperature, and effect of oxidant H_2O_2 concentration were investigated leaching process optimization. Using lixiviant of 5 M HCl, a pulp density of 500 g/L, temperature 75 ^{0}C, agitation speed of 400 rpm and time for 120 min optimum leaching was achieved (Swain et al., 2016a). Swain et al. have observed the cullet size of LCD has a significant effect on the leaching of indium, hence along with the above condition for quantitative leaching the LCD cullet size should keep at ≤ 0.3 mm (Swain et al., 2018).

For the realization of industrial recovery of indium, purification of leach liquor either from acidic leaching or from bioleaching of waste LCD is extremely important has been herewith reviewed. Indium purification by solvent extraction using different extractant like D2EPHA and Cyanex 272 from ITO bearing leach liquor has been reported in the literature (Chou et al., 2016; Yang, 2015; Yang et al., 2013). Recovery of indium from the ITO etching solution by solvent extraction using D2EPHA has been investigated by Chou et al. (Chou et al., 2016). Mainly the ITO etching solution was mixture Al-Ce-Cr-Fe-In-V in acidic HCl solution was treated through the simple solvent extraction process. Average 92% of indium recovery by 0.3 M of D2EPHA at O/A = 1, in pH range 1.0–1.5 was achieved along with other Al-Ce-Fe impurities. The strategy was extraction of indium including impurities to the organic phase, followed by selective scrubbing of impurities and purification of indium. The strategy for scrubbing out Al-Ce-Fe using 2 M or more HCl ended with Fe contamination in strip solution (Chou et al., 2016). Yang et al. have attempted to recover indium from discarded FPD panel glass by solvent extraction. Yang et al. have used HCl or H_2SO_4 leaching-indium purification using D2EPHA as extractant-HCl or H_2SO_4 as stripping route. Yang et al. also followed the same strategy as Chou et al. As reviewed above acid leaching was proficient for dissolution of indium from waste LCD, but solvent extraction was not effective for getting pure indium. As D2EPHA was an efficient extractant all the impurities like Al, Cu, Fe, Sn and Zn along with indium were extracted. In the reported indium extraction strategy scrubbing is an important stage for purification of indium, but when HCl or H_2SO_4 was used for scrubbing out the impurities, proficient selectivity was not indicated. Their result indicates that the proposed process is not efficient enough to get very pure indium (Yang, 2015; Yang et al., 2013). Virolainen et al. applied solvent extraction for indium recovery from ITO etching solution from an LCD recycling perspective. Similar to Yang et al., virolainen et al. have used D2EPHA as extractant and indicated the D2EPHA-HCl, respectively are hardly selective for extraction and e stripping (Virolainen et al., 2011). Chang et al have investigated indium recovery from waste LCD by solvent extraction and hollow fiber supported liquid membrane where D2EPHA was used as extractant both in solvent extraction and supported liquid membrane processes. Unlike solvent extraction process indium extracted efficiently by a supported liquid membrane but selective stripping was the challenge (Feng-Chi et al., 2016). Kang et al. reported the recovery of indium from etching waste by solvent extraction and electrolytic refining, but they have used a solid cake from ITO etching industry (Kang et al., 2011). In contrast to the process reported above, followed by leaching Kang et al. has precipitated out major impurities like aluminum and molybdenum by NaOH. Then indium was purified using PC88A as extractant and stripped using HCl. The resulting indium solution was further purified by electrolytic refining and 99.997% pure indium metal was recovered (Kang et al., 2011).

Swain et al. reported indium purification by solvent extraction both in laboratory scale and industrial scale from ITO etching solution, which can be used (subject to suitable modification and verification through experimental studies) for indium recovery from leach liquor of waste LCD (Swain et al., 2015a, b). As reported by this process impurities like tin, molybdenum can be scrubbed by Cyanex 272 followed by the indium can be purified using D2EPHA as an extractant. Mainly the reported process is purification and concentration of indium by solvent extraction. The strategy used for indium purification is first impurities were scrubbed by Cyanex 272 in extraction stages followed by indium was purified by D2EPHA. Swain et al. have reported ≥ 99.9% indium recovery from impure leach solution using the scrubbing-solvent extraction-stripping-cementation route. The impure leach liquor which contain 1.8–3.99 kg/m^3 of indium, 0.04-0.05 kg/m^3 of tin, 0.46–62 kg/m^3 molybdenum, 0.38–6.11 kg/m^3 of copper, and 1.00–1.35 kg/m^3 of aluminum was investigated for the industrial process development for indium recovery (Swain et al., 2015a, b). As reported, from leach liquor molybdenum and tin was scrubbed out using Cyanex 272, then indium was efficiently extracted using D2EPHA through scrubbing pure indium solution was recovered. From recovered indium solution through cementation using aluminum metal at 90–100 °C pure indium sponge (≥ 99.9%) was recovered. Even copper nano-powder was recover followed by indium recovery though cementation route (Swain et al., 2016b). Precisely, through hydrometallurgy technique using the following routes, indium can be recovered. (i) Leaching-selective precipitation, (ii) leaching-selective cementation, (iii) leaching-solvent extraction-cementation, and (iv) leaching-solvent extraction-electrowinning. Leach-liquor can be generated by conventional acid leaching or bio-leaching.

All the solvent extraction process investigated can be summarized in two different process flow diagram shown in Fig. 11(a–b). The figure by principle summarizes two different strategies for indium purification, i.e., (i) selective scrubbing of impurities from the loaded solvent after extracting all possible metal from leach liquor (Fig. 11a), (ii) scrubbing out the impurities by a solvent followed by selective purification of target metal indium (Fig. 11b). Fig. 11(a) depicts extraction of indium and other impurity metal altogether by solvent extraction using D2EPHA, followed by scrubbing the impurities from loaded D2EPHA, which would provide pure indium solution through suitable stripping. Fig. 11(b) depicts extraction selective scrubbing of the impurity metal by solvent extraction using Cyanex 272, followed by indium purification by solvent extraction using D2EPHA as an extractant. Further stripping from loaded D2EPHA can provide pure indium solution. The process presented in Fig. 11(a) has an important drawback like lack of selectivity in the scrubbing of impurity from loaded D2EPHA. Whereas the process presented in Fig. 11(b) selectively scrub out impurities from leach liquor which finally provide better purity in the indium purification process.

Solvent extraction alternative for purification indium from leach liquor has rarely been investigated. Although the ion exchange or solid phase extraction can be a potential alternative to solvent extraction for indium purification, rarely been reported. A couple of reports has been published for indium purification by ion exchange process is reviewed below. Hasegawa et al. reported the selective recovery of indium from the etching waste solution of the FPD fabrication process by solid phase extraction system. The process includes the application of a metal-selective ligand immobilized onto silica gel or polymer substrates used for selective extraction of indium from solution resin (Hasegawa et al., 2013b). Tsujiguchi et al. used ion exchange for the recovery of indium in an industrial scale (Tsujiguchi, 2012). Assefi et al. reported selective

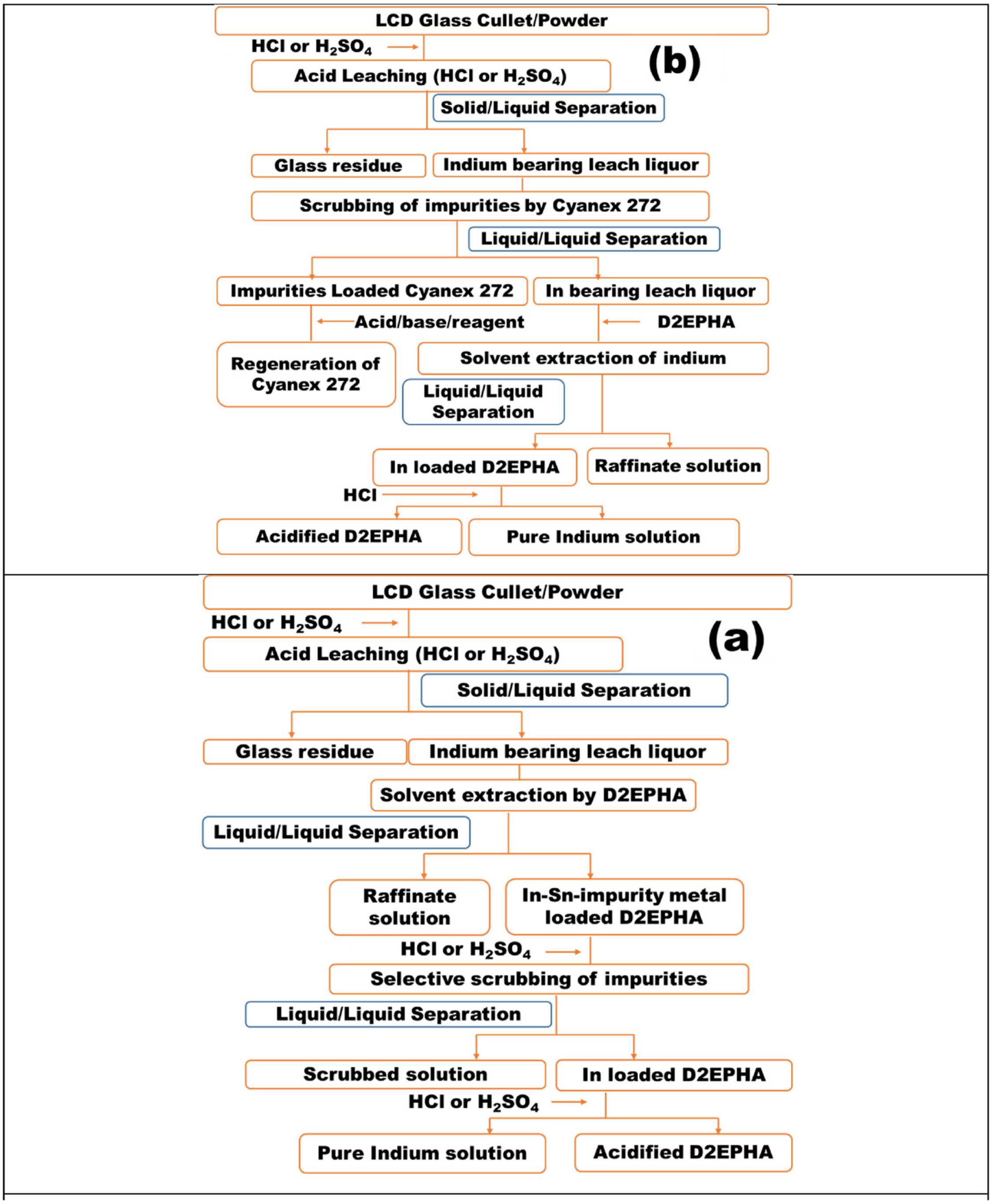

Fig. 11. (a) Selective scrubbing of impurities from loaded solvent (D2EPHA) after extracting all possible metal from leach liquor (ii) Scrubbing out the impurities by a solvent (Cyanex 272) followed by selective purification of target metal by solvent extraction (D2EPHA).

indium recovery from waste LCD panel using macroporous polystyrene-divinylbenzene resins (Lewatit® TP 260, Lewatit® TP 208 and Amberlite® IRA743) (Assefi et al., 2018). Waste LCD was leached using HCl: HNO_3 at a ratio of 3:0.5 M applying ultrasonic waves. From leach liquor, indium was recovered using three different macroporous styrene-divinylbenzene resins (Lewatit TP 208, Lewatit TP 260 and Amberlite IRA 743) were used for indium recovery from LCD scraps (Assefi et al., 2018).

Indium recovery from waste LCD leach liquor by precipitation or cementation without further purification either by solvent extraction or ion-exchange resin can be a feasible strategy has been investigated by a couple of authors. Li et al. have proposed a pure indium recovery method from ITO target using the leaching-cementation route for indium recovery (Li et al., 2011a). Quantitative leaching of indium yield from ITO powder size of less than 75 µm, the H_2SO_4 concentration of 100 g/L with liquid to solid ratio of 8–12 at 90 °C for 2 h along with 8% tin. Followed by a pure indium sponge was recovered using zinc plate cementation at pH 1–1.5 and 65 °C (Li et al., 2011a). Although it is the simplest possible route for indium recovery, the target was a pure chemical adds disadvantage to studying and minimizes industrial recovery perspective. Rocchetti et al. also reported a similar kind of technique for indium recovery (Rocchetti et al., 2016). Recovery of indium from discarded cell phones LCD screens has been investigated by Silveira et al (Silveira et al., 2015). Fig. 12 shows complete recycling flowsheet developed by Silveira et al. In their process LCD screen were manually separated from polymer frame, connector, diffusive sheet,

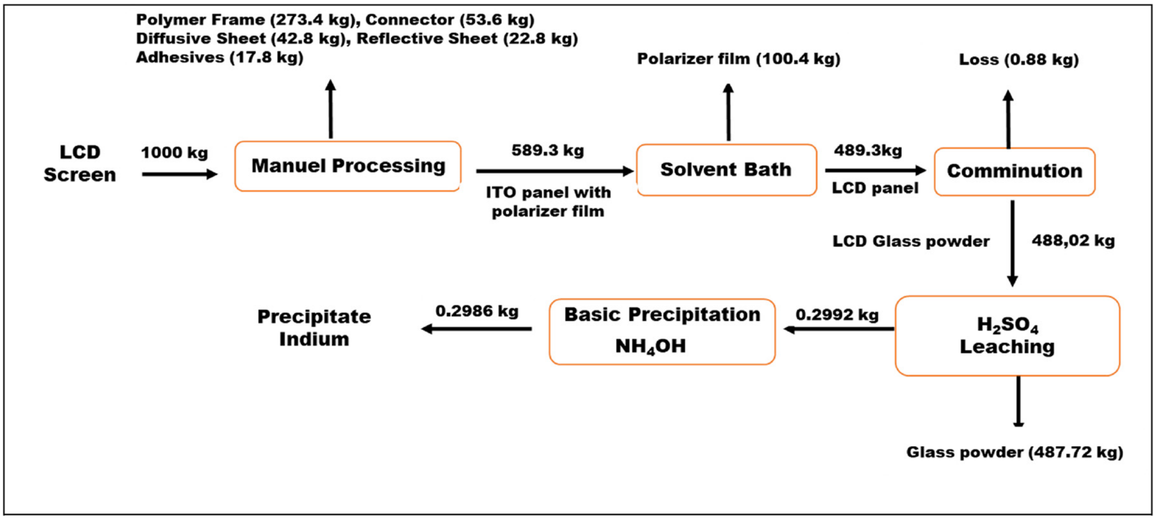

Fig. 12. Flow diagram for recovery of indium from discarded cell phones LCD screens and overall mass balance of the process (developed by Silveira et al. (Silveira et al., 2015)).

reflective sheet, and adhesives. The LCD panel was put in an acetone bath to separate polarized film. The ITO bearing LCD waste was size reduced by baking powder. The waste LCD powder was leached with H_2SO_4, finally, then the leach liquor was precipitated as $In(OH)_3$ using ammonia. The complete flow diagram with mass balance represented in Fig. 12. Fig. 12 indicates that from 1000 kg of LCD waste about 0.3 kg of $In(OH)_3$ was recovered. From purity perspective, the process may be associated with challenges but from the indium recovery point of view, it is an interesting process which can be feasibly industrialized(Silveira et al., 2015). Pure indium recovery can be achieved through several routes, like; precipitation, cementation, electrowinning direct after leaching, from leach liquor or through purification by solvent extraction from leach liquor. Several authors have reported the purification process is reviewed below.

9. Future dimensions and recommendations

Above discussion and review provides the following challenges and the opportunity for LCD recycling, and the critical metal indium recovery. Hence, following a recommendation made in general of e-waste recycling for the efficient circular economy, better environment, and green energy.

(i) The rate of recycling of e-waste versus EOL WEEE generation in the alarming state worldwide needs attention from policy, management, and technology development perspective.
(ii) A developed nation needs an increased rate of e-waste recycling, the devolving needs to develop better waste management strategy and follow the rate of recycling.
(iii) When formal recycling exists mainly dismantled manually, as research clearly evidence the health hazard, hence automated dismantling needs to be developed.
(iv) As indium is a critical metal not only for EU but also for all the industrially developed nations and going to remain critical for green energy and low carbon economy, extensive recycling and indium recovery from LCD waste is important for the successful circular economy and urban mining.
(v) As only less than 1% indium bearing waste being recycled and industrially feasible process for indium recovery from LCD waste hardly available, the mass production capable process needed to be developed. The developed process can bridge the gap between lab scale process and mass production capacity, and waste LCD target and pure ITO target.
(vi) As pyro-metallurgy is highly energy intensive, adverse carbon economy, limiting cleaner production technology and needs expensive industrial machinery, focused on hydrometallurgy can successfully handle the challenge as small-scale hydrometallurgy plant can handle the disadvantages of the pyro-metallurgy process. Based on the above review the possible hydrometallurgy process can be generalized as given in Fig. 13.
(vii) As informal recycling encourages waste flow from a developed nation to Asia and Africa, which adversely affect the global environment and local community health, needed to be restricted.
(viii) Cost effective process development is essential for a circular economy and urban mining notion, which can attract business houses for the crucial e-waste recycling and indium recovery.
(ix) Research and innovation for sustainable access to the secondary raw materials will continue to play a fundamental role in maintaining the competitiveness of the industry. Hence, facilitating the transition to a circular economy and developing low carbon technologies is absolutely recommended.

10. Summary

Per capita e-waste increasing rapidly as well as ITO bearing waste LCD screen. Clean energy per capita consumption consequently uses of the critical energy metal like indium set to increase rapidly. The volume of e-waste generation versus e-waste recycling in an alarming state, depletion of primary resource, supply chain crisis for indium, irreplaceability of indium for technological application multiples the issue with indium. Through EU leading the developing policy, stringent environmental regulation and goal for recycling rate as we as some Asian Pacific nation promoting the same, still around the globe all those are either in a primitive stage or not at all existing. Circular economy and urban mining still in the context of indium almost non-existence. As raw materials are crucial for strong industrial growth and competitiveness, in the scenario of critical metals, the circular economy is vital for sustainable processing, reuse, recycling, and recovery technologies. To meet all challenges proficiently, the profound recycling of e-waste in general and waste LCD in particular concurrently can address multi-dimensional issues like e-waste management and recycling, indium recovery and circularize economy, landfill and urban mining, waste crime and informal recycling, environmental crisis and occupational hazard, and low carbon and green energy. Our thorough literature investigation suggests that integrated industrial indium recovery process from e-waste hardly been established. Hence, the above

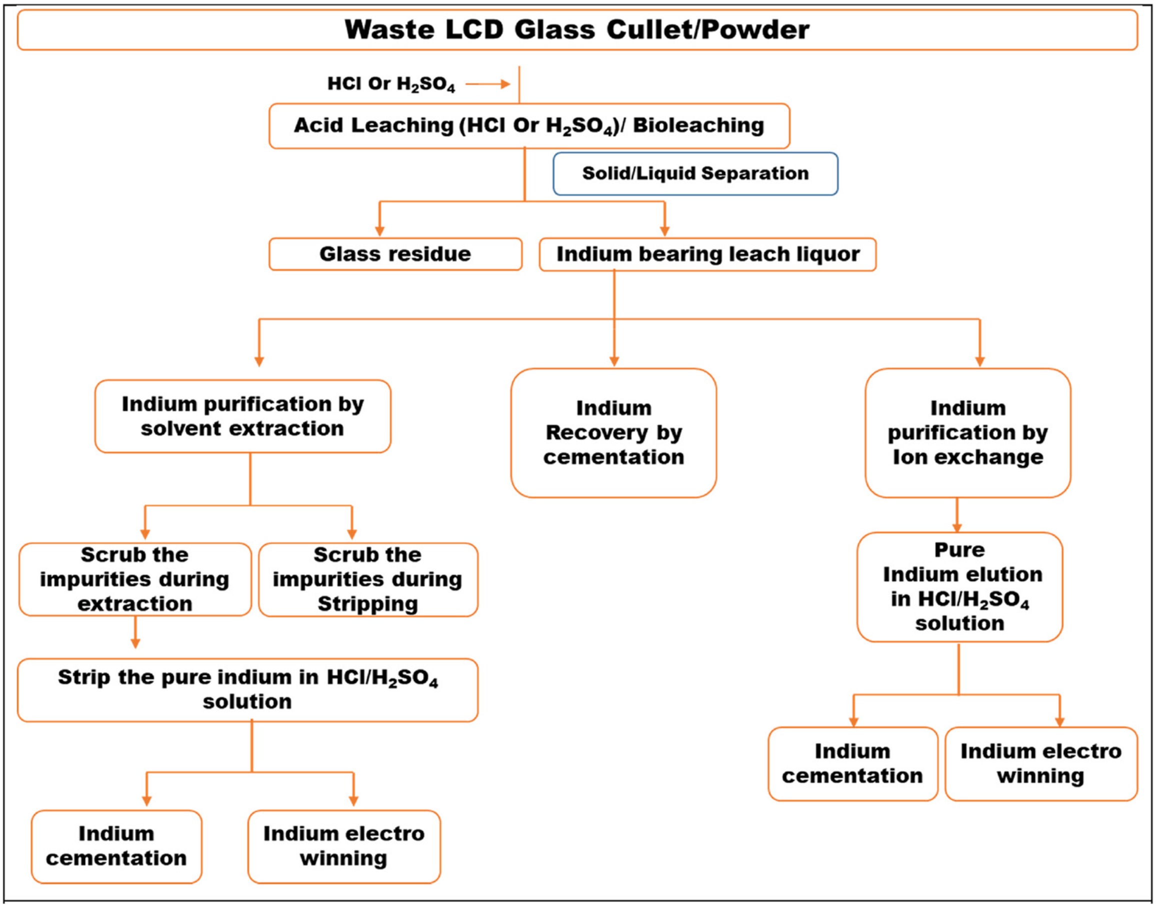

Fig. 13. An envisioned strategy for possible hydrometallurgy recovery of indium from e-waste or waste LCD.

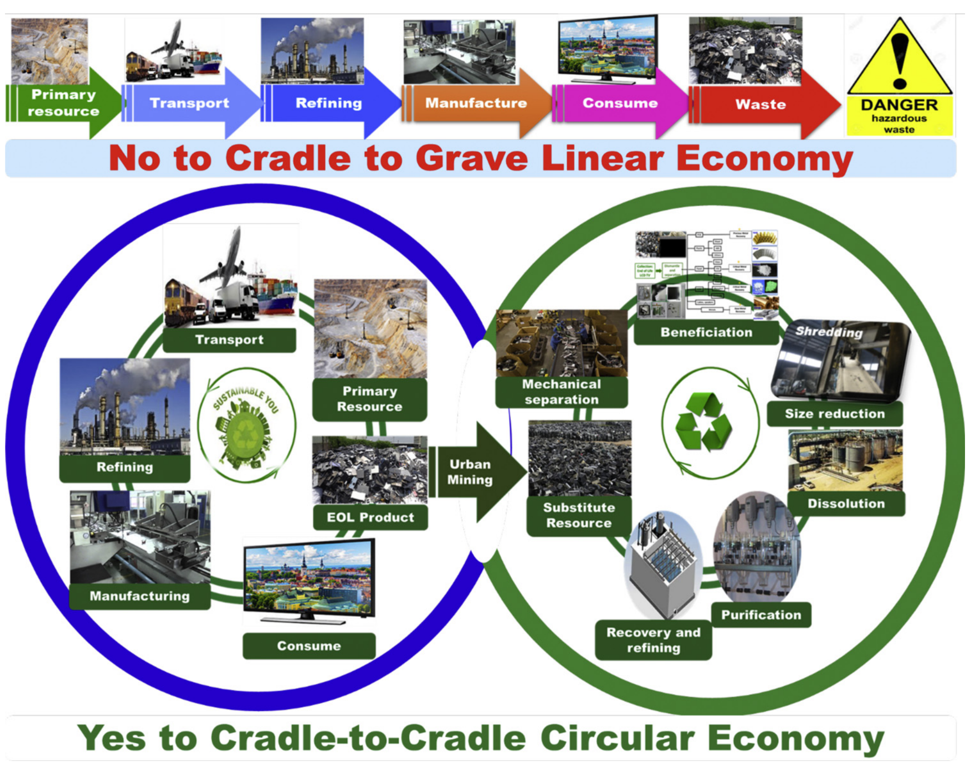

Fig. 14. Schematic for feasible circular economy instead of the linear economy and the most sustainable generalized process for e-waste (e-waste in general and waste LCD in particular) recycling, which can easily be practiced and implemented.

recommendation concurrently can resolve the e-waste challenge and can provide a great opportunity to address the supply chain critical issue for indium. Proficient and profound recycling not only address the environment, energy, and economy but also create employment opportunities. Hence, the development of industrially feasible and eco-efficient process from dismantling to recycling in need of the time and need of the generation. Indium a critical metal; scarce in primary sources but abundant in e-waste, critical in supply chain but crucial to green energy, lacking in recycling rate but progressive EOL waste generation, poses a threat to ecosystem/habitat but potential to circularize the economy, primarily as a by-product but potential urban mine, both a challenge and an opportunity, concurrently. Most practiced cradle to grave linear economy is no more sustainable and adaptable because of e-waste and its impact. The cradle to grave linear approach not only an environmental hazard but also an economic threat. As metal has infinite possibility and potential for recycling, the circular economy should play an important role. In Fig. 14 the drawback of linear economy and advantage of circular economy postulated. Fig. 14 summarizes feasible circular economy approach that can easily be practiced and generalizes the most sustainable recycling process for e-waste (e-waste in general and waste LCD in particular).

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