

RECOVERY OF PRECIOUS AND OTHER METALS FROM ELECTRONIC WASTE: A REVIEW

Abstract

Printed circuit boards (PCBs), which are essential parts of electronic equipment, are regarded as major e-waste sources that pollute our environment. These materials have a detrimental impact on the health of humans, animals, and plants since they are made up of hazardous heavy metals. To recover the valuable and eliminate the dangerous metals from e-waste, a number of physical and chemical methods have been used. The old physical and chemical methods of preventing the buildup of e-waste have been shown to have intrinsic disadvantages, such as the creation of hazardous gases and toxic byproducts. Additionally, the current environment places significant obstacles in the form of high execution costs and additional waste production from traditional approaches. By using environmentally friendly techniques like biosorption and bioleaching, these constraints may be circumvented. Consequently, this review's goal is to assess the potency of biosorption and bioleaching methods in recovering the metals from e-waste in addition to other techniques.

Keywords: Printed circuit boards, Biosorption, Bio-leaching, E-waste.

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I. INTRODUCTION

One of the top environmental issues faced by the global community is the generation of a huge amount of e-waste around the world. E-waste can be termed as the discarded electronic utilities at the consumer's end encompassing cell-phones, stereo systems, computers and other domestic electronic appliances. It may be mentioned that most of the e-waste is disposed in to the landfill sites informally. Nearly 40 MMT of the e-waste was generated all over the world due to the increase in usage of the electronic equipment's and rapid innovation in the technology [1]. It is worth to note that out of the waste generated only about 20 percent is recycled as per the estimation of environmental protection agency [2]. E-waste contains numerous toxic and hazardous substances which adversely affects the environment and can lead to the severe health problems in humans [3]. Contrarily, e-waste has precious metals such as Ag, Au, Pd, Cu, Co too as its components and priority should be given for the recovery of these metals [4]. Therefore, sustainable and eco-friendly approaches are requisite to address the disposal of e-waste. Generally, the land-filling is employed for the disposal of e-waste. One of the major threats comes from the land-filling procedures used for the disposal of e-waste. Drawback of which is that the toxic metals present in it mitigates to the human body through soil-crop-food route. Among e-wastes Printed Circuit Boards (PCB's) are mainly composed of Cu, Fe, carbon materials, organic resin and glass materials. Precious metals such as Au, Ag, Pd are also incorporated in the integrated circuits (IC's) due to their high chemical stability and conductance, [5] and are an integral part of all electronic appliances.

Hence the recovery of these valuable metals from the PCB's waste needs to be prioritized. Many conventional and advanced methods such as incineration, land-fill, pyrolysis, chemical leaching are considered by the researchers for the recovery of metals from waste PCB's as well as to minimize the adverse effects on the environment. A number of reviews [6-8] are already available in the literature; hence a brief discussion of the techniques has been made here in this review. However, a detailed discussion of some of the environmentally friendly and sustainable recycling techniques to recover the metals from PCB's waste has been made in this article. Furthermore, the factor affecting these techniques has been discussed too in this review.

II. RECYCLING TECHNOLOGIES FOR METAL RECOVERY FROM PCBs

At present, PCB's waste can be recycled using various conventional and advanced methods. Land filling and incineration methods, where a very low amount of energy is consumed [9] are widely used but the environmental constraints of these methods made them inappropriate in the current scenario. On the other hand, metallurgical processes for the recovery of metals from the PCB's waste has also been utilized by the researchers [10]. Though pyrometallurgy is widely used but the high energy (in form of heat) requirement is a constraint from sustainable perspective. Hydrometallurgical process such as chemical leaching has been extensively used too [11, 12]. Besides these, a limited use of biological methods such as bio-leaching and biosorption utilizing the microbes for the leaching purposes of metallic fractions from PCB's waste has also been made by the researchers. Therefore, a discussion with advantage and disadvantages of the techniques utilized by researchers is made in the subsequent paragraphs [13, 14].

- 1. Incineration:** The calorific values of PCB's waste were converted into energy by subjected them to the heat i.e. by releasing gas with non-metallic fraction. The original volume of PCB's retained about a half through this method. Being simplistic, incineration was extensively adopted by the researchers world-wide. The major constraints when subjected to the combustion are toxic substances such as heavy metals, formation of dioxins and a considerable amount of fly-ash which are disposed into the environment without any treatment. Moreover, the metallic fractions of Cd, Pb, Zn, Cu and Ni present in the PCB's waste are also disposed into the environment upon melting at their respective melting points. Cu also behaves as an catalyst during the process and gives rise to the formation of dioxins during incineration [11]. Additionally, fly-ash or bottom ash is also produced during the process which increases the pollution level of the environment and needs coupling of other methods for its disposal. Since toxic and harmful substances are disposed into the environment during incineration, hence, it cannot be termed as an environmental-friendly approach. Moreover, the construction cost for an incineration set-up is very high which is also a barrier in terms of cost-effective approach.
- 2. Land Fill:** Being simplistic, land filling is used from a long time globally to recover the metals. Dumping of PCBs waste in an open ground land and sealing it, is the mechanism followed during land-filling. Over the time, the metals in the formed leachate were recovered. However, it is not an efficient and sustainable method because, the land used for the filling purposes is no more appropriate for any other work. Moreover, the risk of leakage from the formed liquid and produced toxic gases contaminate the ground which further mitigates to the human body through crop to food route [15]. Hg and Pb which are well-known toxic heavy metals found in the land-filled set-ups can lead to the aquatic systems and poses a threat to the marine lives [16]. Therefore, the disposal of PCBs waste through land-filling poses extreme risks to the environment as well as to the aquatic life. Consequently, the use of some alternatives to reduce the adverse environmental impact of land-filling should be prompted for the sustainable recovery of the metals.
- 3. Metallurgical Processes (Smelting and Chemical Leaching):** Metallurgical processes are widely used to recover the metallic fraction from PCBs waste. In metallurgical processes, metals are melted by heat in absence of oxygen (pyrometallurgy or smelting) or are dissolved by using some solvents (Chemical leaching) and further can be distinguished on the basis of their chemical and metallurgical properties.
 - **Pyrometallurgy:** Pyrometallurgy or smelting, has emerged as a conventional route for the recovery of the metals from PCBs waste in the recent decades. In this method, the PCB's are directly subjected to the heat (400-900°C) in absence of oxygen and the resulting ash on the completion of the process is found to be rich in metals. However, a considerable amount of solid fraction in the form of slag, loss of metallic part during heat-treatment and lower extraction rate of Aluminum and Iron were major barriers in the implication of this technique [17]. On the other hand, the release of hazardous gases is also a drawback of this process and therefore, it cannot be termed as an eco-friendly approach.
 - **Chemical Leaching:** Chemical leaching processes have gained attention in recent years and can be employed as an efficient method over pyrolysis by the researchers. Chemical leaching, where usually acid-leaching is mostly selected, and the metals

were recovered following the leaching route. [18]. In comparison to the caustic acid, leaching utilizing aquaregia, thiourea and thiosulfate can be termed less toxic to the environment. On the other hand, cyanide leaching is being cut-off as a leaching route because of its acute toxicity. After leaching, various metal recovery routes such as precipitation and electrochemical routes for metal deposition are utilized. Park et.al [19] recovered precious metals silver, gold and palladium from PCB's using aquaregia as a leachant with a metal to leachat ratio of 1:20. Ag (98%) and Pd(93%) were recovered successfully in the first stage, whereas, to recover the Au (97%), toluene was employed by the authors for the liquid-liquid extraction route after the leaching was completed. In another study, Quinet et.al [20] used cyanide leachants (NaCN) to recover the Au and Ag and reported a high recovery of the precious metals. But on the other hand, emission of nitrogenous like toxic gas when utilizing aquaregia as an leachant is also a serious concern from the environment point of view. Thiourea is unstable in acidic medium, and its easy oxidation easily to form a toxic compound formamidine disulphide also made its use inappropriate and are the main disadvantage of the chemical leaching processes. Therefore, a sustainable and eco-friendly approach is required to recover the metals from PCBs waste.

4. Bioleaching: Bioleaching is an innovative and non-traditional leaching based approach in which a diverse group of microbes and fungi are utilized to recover the metals by dissolution from PCBs waste. [21, 22]. The excretion of organic acids by the microbes get solubilized the metals and leads to a complex formation between the excreted acids and the metallic fraction of the waste. In this process, the metals present in the PCBs waste get interacted with the living or dead microbes or fungi. Various microbes for the solubilisation of metals such as thiobacillus, ferrooxidans and pseudomonas and fungi namely Aspergillus, pleurotus florida etc. were successfully applied for a wide array of metals like Zn, Cu, Pb, Cd, Fe, Li etc. with high recovery and improved performance. by excreting organic acids; these acids then form complexes with heavy metals. Kaliyaraj et al. successfully recover Zinc, Calcium, Nickel, Iron, Silver, Lead and Aluminium from PCBs waste utilizing streptomyces albidoflavus TN10 and observed the simultaneous recovery of all metals in which zinc and calcium was recovered maximum with percentage of 82 and 72%, respectively while the iron with 42% recovery marked the minimum fraction. [23]. Hussain et al.[24] utilized desulfovibrio fructosorans and desulfovibrio piger to reduce the sulphate from sulphate rich solutions for the incubation period of 60 days. The authors found that almost total sulphates were reduced within an incubation period of 10 days. It means that sulphate can be reduced using sulphate reducing microbes. In a work, carried out by by Murugesan et al. it was found that bio-leaching procedure to recover Cu by ferrooxidans was resulted in high recovery (96%). Therefore it can be inferred that ferrooxidans can favored the copper recovery from the leachates. [25]. Bioleaching makes a vital role of bacteria in Fe^{3+} regeneration. In an another study by Narayanasamy et al. [26] Aspergillus niger was also utilized for the extraction of metals as the employed fungi produced a great amount of acid in bio-leaching process and the recovery of the precious metals such as Ag and Cu from PCBs waste has been found to be more favorable in acidic conditions. The list of microbes and their metal recovery efficiencies from the PCBs through bioleaching process are given in Table 1.

5. Biosorption: Biosorption can be termed as the potential of biomass to bind the metals from the processed e-waste using microbes from the aqueous solutions even if they are present in lower concentrations. [27, 28]. Various physicochemical parameters viz. pH,

temperature, contact time, microbes composition made the process very complex. [27, 29]. Different heavy metals e.g. Cd, Ag, Pb, Ni etc. by the application of biosorption using bacterium and fungi were studied by several researchers. In a recent study, Kaur and co-workers [30] studied the biosorption of Cu and Fe using *Pleurotus florida* and *Pseudomonas* spp. From electronic waste and it was found that 97 mg kg^{-1} and 94 mg kg^{-1} of Cu and Fe was biosorbed by *Pleurotus florida*, whereas, an increased biosorption (98.00 and 96.20 mg kg^{-1} for copper and iron, respectively) was observed in case of *Pseudomonas*. Sheel et.al. [31] studied the biosorption of gold from e-waste by using the combination of ammonium thiosulfate and *Lactobacillus acidophilus* and recovered 85% of gold from ammonium thiosulphate. Hence, biosorption using microorganisms also emerge as an effective tool for the recovery of metals from e-waste. It is a sustainable and eco-friendly approach as no need for chemical additions and can be suitable for the uptake and removal of various metals simultaneously.

III. CONCLUSIONS

Recycling trend for the recovery of precious metals as well as proper disposal of the hazardous substances from the PCBs waste to reduce the environmental load is an effective approach. Conventionally, the smelting of the PCBs waste was utilized for the recovery of metallic fraction as well as for the disposal of it. However, the negative impact of this method on the eco-system makes it inappropriate in the present scenario. Besides this, the incineration and land-fill methods to recover the metals are also not suitable from the environmental perspective. Contrarily, the bio-leaching and biosorption being green and sustainable pull the attention of the researchers. Therefore, on the basis of the methods discussed in this review, it can be evaluated that bio-leaching and biosorption has emerged as a promising and sustainable approach to be used in metal recovery from e-waste due to their minimal environmental impact. The improvement of bioleaching efficiency and the selection of various bacterial combinations to effectively increase the potential of these techniques are the giant challenges for the researchers in future.

Table 1: Different Microorganism Used For the Metal Recovery from E-Waste by Bioleaching.

Microorganism used	Target Metal	Recovery percentage	E-waste	References
<i>Pseudomonas fluorescens</i> ; <i>Pseudomonas putida</i>	Au	44	PCB	[32]
<i>Pseudomonas fluorescens</i>	Au	54	PCB	[33]
<i>Aspergillus niger</i> MXPE6 <i>Aspergillus niger</i> MX7	Au; Cu	87; 24	PCB	[34]
<i>Purpureocillium lilacinum</i> , <i>Aspergillus niger</i>	Cu; Al; Zn; Pb; Sn	56.1; 15.7; 49.5; 20.5; 8.1	PCB	[35]
<i>Acidithiobacillus caldus</i> <i>Sulfobacillus thermosulphidooxans</i>	Cu, Zn	96	PCBs	[36]
<i>Acidithiobacillus ferrooxidans</i>	Cu	96	PCB	[25]
<i>Acidithiobacillus</i> sp.	Cd; Cu; Ni; Zn	93; 53; 48.5; 48	PCB	[22]

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