**An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE.**

This article highlights speciﬁc gaps in the available technology for solving the e-waste issue, and recommends a hybrid strategy as the best available approach.

1. Rapid population growth and technological advancement have increased the purchase, use, and discarding of electrical and electronic equipment’s (EEEs), resulting in the generation of a massive amount of WEEE
2. Globally, an estimated 41.8 million metric tonnes (MT) of WEEE were generated in 2014 (Balde et al., 2015) [Supplementary Information (SI)-Table 1)].
3. huge amount of WEEE is illegally shipped from developed nations to developing ones
4. The major portion of this e-waste is processed by traditional or crude methods in the informal sector
5. These crude processing methods consist mainly such as, breaking, acid leaching and

open burning which lead to the release of toxic gases and other contaminants into the atmosphere (Fu et al., 2011; Birloaga et al., 2013; Zhang et al., 2014), heavy metals and other pollutants into soil and groundwater (Quan et al., 2014), where they can easily persist for a long time (Awasthi et al., 2016a). Additionally, these pollutants can be transported and accumulated inside plants system, and thence through dietary intake to animals and/or humans, (Awasthi et al., 2016b

1. Approaches to separate metals from non-metallic portion like electrostatic, and magnetic separation, vacuum metallurgy, hydrometallurgy has been applied but they are either nor cost-effective or not ecofriendly.
2. mechanical recycling requires signiﬁcant capital investment; chemical methods—cause secondary pollution, and biological methods are slow (Ilyas and Lee, 2014a; Jadhav and Hocheng, 2015; Karwowska et al., 2014).
3. The primary aims of any WEEE recycling method are to mitigate the negative environmental and public health eﬀects of hazardous substances and to recover valuable materials
4. Mechanical recycling of WEEE includes—three main approaches, (a) Dismantling: which focuses on removing valuable and hazardous components (Movilla et al., 2016), (b) Upgrading/repairing: which focuses on re-using desirable materials, and (c) Reﬁning: recovering materials and returning them to their normal life cycle (Zeng et al., 2016; Zlamparet et al., 2017).
5. Chemical leaching process is that useschemicalsandcomplexometry, suchasaligand thatcanattachtoa speciﬁc metal. Disadvantage- the building of such leaching reactor based on highly corrosive HNO3 and aqua regia, which limits its feasibility at industrial scale
6. the use of microbial agent for the removal of metals from WEEE is biological recycling. Three major microbial groups—autotrophic bacteria (e.g. Thiobacillus sp.), heterotrophic bacteria (e.g. Pseudomonas sp., Bacillus sp.) and heterotrophic fungi (e.g. Aspergillus sp., Penicillium spp.)—are frequently being tested for the bioleaching and bioaccumulation of metals (Mishra and Malik, 2012; Shah et al., 2015).
   1. Disdvantage: the heavy metals can trigger a cellular response that can inhibit metabolic pathways, and even very low concentration of heavy metals can aﬀect the morphology of fungal strains and also inhibit fungal growth. High metal concentrations can even cause protoplasmic poisoning, and denaturation of proteins and nucleic acid
7. in order to solve the WEEE issue subjected to environmental protection and resource recycling, Zeng et al. (2015) proposed an integrated mobile recycling plant, combined dismantling processes, then mechanical crushing, electrostatic separation, multi-level magnetic separation, cyclone classiﬁer, attached air cleaning equipment’s and vibrating screener are well equipped. The main beneﬁt from such type of WPCB recycling plants has no release of liquid waste and smoke gaseous, although only needs some manpower to operate and because this process is highly automated.
8. Although bioleaching appears to be the best approach overall, before it can be seriously considered for widespread implementation, more research needs to be done, to determine the optimum conditions and inputs, such as suitable nutrients and their ratios, pH, temperature, O2 as well as an appropriate acid/base.
9. A study by Qu and Lian (2013) found that organic acid can be used for metal recycling and recovery, and that such organic acid could be produced bymicrobes, possibly reducing the overall cost of this approach. In this regard, as we discussed earlier, metal bioleaching has great potential, because it can either enzymatically reduce highly oxidized metal compounds, or produce organic acids, including hydrophilic reactive groups (Ilyas et al., 2013). Alternatively, many bacteria can be used as a leaching agent for the recovery of precious metals, for instance: Silver, Palladium and Gold from WEEE (Tran et al., 2011). These primitive recycling yard—referred to as the informal recycling sector—have caused signiﬁcant environmental damage and led to health problems in the workers (Awasthi et al., 2016a, 2016b). Furthermore, the toxic substances released during the process can cause health problems in the general population in the area surrounding the workshop. Much of this damage is caused by lack of public awareness and the exportation of e-waste from developed countries like, the United States, and Japan to developing countries, like India and China (Manomaivibool, 2009; Wong et al., 2007; Awasthi et al., 2016c; Awasthi and Li, 2017).
10. Panda et al. (2015) estimated that a combination of bio-reduction and chemical leaching can extract about 61.9% of copper metal after 39 days—and suggested that this approach is feasible for treatment. Qu and Lian (2013) found that, citric and oxalic acids were the main lixiviants for bioleaching of rare earth elements using Penicillium tricolor. Sahni et al. (2016) studied a hybrid technology based on Chemo-biohydrometallurgy (Chromobacterium violaceum)—to recover metals from refused mobile SIM cards. It is clear that, using some hybrid combination of physical, chemical and bioleaching methods could be an eco-friendly, economically feasible solution to the WEEE processing problem
11. Unfortunately, although several conventional methods are available, these sometimes merely transfer the pollutants (as primary pollution) from one place to another (as secondary pollution).
12. In this context, many researchers have suggested that, the addition of an acid/solvent extractant to the bioleaching solution would result in faster and more eﬃcient metal extraction (Ilyas and Lee, 2013, 2014b).
13. Xu et al. (2013) suggested that closed-loop recycling helps to minimize the risk of human-health and global-warming eﬀects, compared to landﬁlling, pyrometallurgy and hydrometallurgy, which can cause signiﬁcant environmental impact. Nevertheless, closed-loop recycling, hydrometallurgy and pyrometallurgy all generate more proﬁts (110–450$/ ton) than landﬁll (45$/ton). Zhang and Forssberg, (1998) said that, the recovery of metals from e-waste could be beneﬁcial in term of both environmental and economic aspects such as, primary metal resources conservation, recovery of plastic&precious metals, and minimization of energy consumption. For example, Goosey and Kellner, (2002) found that the recovery of aluminium (95%) and copper (85%) produces the highest energy-savings ratio.
14. A sustainable and environmentally sound recycling industry could attain maximum reuse of secondary resource materials in developing countries (Natalia and Colin, 2015), while improving the environment and human health, and providing employment opportunities for their citizens. For example- Li et al. (2016) suggested that the Chinese WEEE market could be manageable, if the government would oﬀer incentives to e-waste recycling enterprises, for instance subsidies, low-cost loans, tax cuts and credits; engage in substantial public awareness campaigns on waste management and environmental protection; and implement public collection systems that would separate discarded WEEE from the general waste stream. Additionally, because a number of enterprises in developed countries have created very advanced recycling, eco-friendly and energy-saving technologies, they could be invited to invest in operations in China, thus generating beneﬁts both for themselves and for China.
15. best method for management of WEEE is re-use, if the e-product is still in usable condition (Zlamparet et al., 2017; Kahhat and Williams, 2010). The second option would be to disassemble the product and ﬁnd out if any individual components are in good enough condition to reuse (Kissling et al., 2013; Kissling et al., 2012). Then, if neither of these options is feasible, the product—or the unusable components of it—would be sent to mechanical recycling. In this context, by considering the mechanical approach, Zeng et al. (2015) deigned a mobile e-waste recycling plant focused on an integrated combination of manual dismantling and mechanical recycling for eﬃcient metal recovery.
16. Oguchi et al. (2012) stated that, the mechanical treatment of WEEE, involving manual dismantling, has proved to be the most promising approach for computers and their accessories. He et al. (2015) argued that, both the cathode materials and Al can be recycled very eﬃciently using such processes.
17. Recent reports have indicated that biological recovery of precious metals has gained great attention. For instance, Nancharaiah et al. (2016)hasextensivelyemphasizedthebio-recoverypreciousmetalssuch as Pd(II) and it is possible to reuse this element catalytic applications. Numerousmicroorganismsare abletoreducethe Pd(II)toPd(0) and this approach is beneﬁcial as it permits easy retention of Pd(0) in bioreactors (Rotaru et al., 2012; De Corte et al., 2012; Deplanche et al., 2012; Hosseinkhani et al., 2012). From this perspective, Nancharaiah et al. (2016) suggested that biotechnology approache for the recovery of

valuable metals from liquid wastes have gained a high reputation in the last few decades because of the cost-eﬀective ability of microbes with speciﬁcformationstosequesterdiﬀusemetals,whichhaveahighmarket potential as a secondary resource. He also warned that, the development of innovative programs for the appropriate and eﬃcient exclusion and recovery of metals from WEEE (including spent batteries, and industrial sewage), applying microbes, needs further study.

1. In other words, a hybrid approach—using a combination of physical, and microbial methods, as well as increasing public awareness and infrastructure investment—has the potential to resolve the critical issues related with the recycling of e-waste and the recovery of metals and other valuable materials containedinit.
2. It has revealed that a hybrid approach could oﬀer a sustainable and eco-friendly platform with a higher metal recycling potential and leaching eﬃciency than any single method. In addition, some problems exiting in both mechanical and biological approach, can be overcome by (1) The development of a microbial consortium by using diﬀerent microbes for extracting diﬀerent metals, and (2) Using microbes based on organic acids to optimize recovery rates. On other hand, combining mechanical recycling (including dismantling) with biological approaches could be one of the best options, although still this area need more improvement for eﬃcient metal recycling.