Microorganisms and Plants in the Recovery of Metals from the Printed Circuit Boards of Computers and Cell Phones: A Mini Review

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Abstract: Most electrical and electronic equipment contain a printed circuit board (PCB), which is the board on which microelectronic components are mounted. The PCBs of obsolete and discarded electrical and electronic equipment are a material of great value due to their high metal content that is of commercial importance (i.e., Au, Ag, Pd, Pt, Ir, Ti, Ge, Si, Al, Cu, Ni, Zn, Fe, Sn, As, and Pb). Hydrometallurgical and pyrometallurgical methods have been used to extract metals from PCBs; however, these methods have energy and environmental disadvantages, which is why in recent years sustainable alternatives have been sought. Among these alternatives are the biological methods that contemplate the use of microorganisms and plants to recover metals from PCBs. In this review, only studies specifying the use of bacteria, fungi, and plants in the recovery of metals from the PCBs of computers and cell phones were considered, since the metallic composition of these plates varies according to the electronic equipment. In addition, the challenges and recommendations for these biotechnological processes to be improved and implemented at the industrial level in the coming years are discussed.

Keywords: electronic waste; phytoextraction; fungi; bacteria; plant

1. Introduction

Waste electrical and electronic equipment (WEEE) incorporate various types of equipment, such as cell phones, musical equipment, video and sound equipment, rechargeable batteries, computers, monitors, printers, computer peripherals, cables, televisions, equipment telecommunications, household appliances, toys, and tools that have ceased to be useful according to the definition of Widmer et al. [1]. Other definitions mention that they are electrical and electronic devices that have been discarded by their owners, that are obsolete or broken, or that have reached the end of their useful life [2]. They have even been defined as a mixture of various metals, particularly copper, aluminum, and iron, covered or mixed with various types of plastics and ceramics [3].

At present there is high consumption of electrical and electronic equipment due to technological advances, which have shortened the lifetime of these devices [4,5]. Such a situation has resulted in millions of electrical and electronic devices being discarded every year [6]. In recent the last decades, worldwide, 20–50 million tons of electronic waste has been generated [7], of which, more than 90% was deposited in open-air dumps or incinerated [5,8]. Improper handling of electronic waste has
caused an environmental and health problem by contaminating air, soils, sediments, bodies of water, and crops [9,10], since these devices contain more than 1000 substances such as Pb, Hg, As, Cd, hexavalent Cr, polychlorinated biphenyls, polybrominated biphenyls, and epoxy resins that have high toxicity [11]. Among the effects of soil contamination by metals (i.e., Cu, Zn, Ni, Cd, Pb, and Cr) from activities related to the treatment of electronic waste, microbial communities have been reported to have significantly reduced their relative abundance compared to uncontaminated soils [12]. This is a situation that could have a significant impact on the ecological function of soil [13].

However, electronic waste is a secondary source of metals, as it contains a large amount of commercially important metals such as Au, Ag, Pd, Pt, Ir, Ti, Ge, Si, Al, Cu, Ni, Zn, Fe, Sn, As, and Pb [14,15], in addition to containing rare earths such as La, Nd, Dy, and Y [16]. For this reason, they are considered an alternative to metal extraction with traditional mining, which, for many years, has caused damage to the environment and has depleted metal resources [17]. Therefore, several countries have promoted new strategies for obtaining metals from electronic waste, which help meet the global demand for metals without depleting mineral resources [18]. Thus, obtaining metals from WEEE seems to be a sustainable strategy; however, the hydrometallurgical and pyrometallurgical processes used in the extraction of metals have energy and environmental disadvantages (by generating corrosive effluents and toxic gases) [8,19,20]. Considering the above and given that to date there is no standard ecological technique available for the recovery of metals from WEEE [8], biological alternatives are being sought that can meet the future needs of the metallurgical industry, without high costs and without affecting the environment [21]. Likewise, ways in which to obtain metals in the form of nanoparticles with higher purity that can be used in the nanomaterial industry are also being investigated [22]. Therefore, in this review, we describe the biological alternatives for the recovery of metals from WEEE using microorganisms and plants, highlighting only the reports in which the printed circuit board (PCBs) of cell phones and computers are used, which is of great importance, since the composition of PCBs varies according to the electronic equipment. For example, the concentration of Cu and Au is lower in the PCBs of televisions than in the PCBs of cell phones [23]. Studies that mix the PCBs of different electronic equipment [24] were not considered, nor were the studies that did not mention the equipment from which the PCBs came.

2. The Printed Circuit Boards of Computers and Cell Phones

A PCB is a flat base (commonly of fiberglass reinforced phenolic resin that functions as an electrical insulator) on which microelectronic components such as chips, semiconductors, and capacitors are mounted. A PCB provides electrical interconnections between components and is included in almost all electrical and electronic equipment [25].

The main role of PCBs is to function as the main processing unit for electronic devices [8]. Most PCBs are multilamellar in nature and contain high concentrations of Cu, Au, Ag, Pd, and Pt [26]. There are different types of PCBs, namely, monolayer, double layer, multilayer, high definition, and flexible multilayer [27]. Unprocessed PCBs are classified according to their flammability, using the abbreviation FR, and the degree of flammability ranges from 1 to 5, with 1 being the most flammable and 5 the least [28,29]. The basic components of a PCB are resin and reinforcement. PCBs of the FR-4 type composed, of multiple layers of epoxy resin with a fiberglass reinforcement and covered with a copper layer, are used in mobile phones (Figure 1a). Meanwhile FR-2 type PCBs, which are made of phenolic resin with a cellulose paper reinforcement and copper coating, are commonly used in computers (Figure 1b), household appliances, and televisions [20,25]. As reported by Yamane et al. [27], the PCBs of cell phones are made up of 63% metals, 24% ceramics, and 13% polymers, while that of computers are 45% metals, 28% ceramics, and 27% polymers (weight%, wt %). The metallic part can contain valuable metals such as Cu, Fe, Al, Ni, Pb, Ni, Ag, Au, and Pd [30] (Table 1).
3. Microorganisms in the Recovery of Metals from the Printed Circuit Boards of Computers and Cell Phones

Before carrying out the bio-recovery process of metals, a pre-treatment is required to obtain the PCBs that will subsequently be in contact with the microorganisms. Pretreatment generally involves dismantling computers and cell phones to obtain the PCBs, followed by reducing the particle size of the PCBs (Figure 2).

The use of microorganisms for the recovery of metals from electronic waste, in most cases, has to do with the ability of bacteria, fungi, and microalgae to degrade or transform contaminants into simpler and less toxic substances [33]. However, two processes occur in the interaction of microorganisms with the metals from PCBs: (1) The mobilization of metals from PCBs and (2) the immobilization of solubilized metals. Some of the microbial mechanisms involved in these processes are bioleaching, bioaccumulation, biosorption, bioprecipitation, bioreduction, and biooxidation [34]. Of these, the most important microbial mechanism is bioleaching, which may involve acidolysis, redoxolysis, and complexolysis [35,36].

Among the most used microorganisms for the metallic recovery of electronic waste are acidophilic bacteria, cyanogenic bacteria, and filamentous fungi. In the case of acidophilic bacteria, the bioleaching mechanism used to mobilize metals from PCBs consists of oxidation and reduction reactions, where energy transfer for bacterial growth occurs through electron transfer. For example, when iron is used as an energy source, biooxidation of ferrous iron into ferric iron occurs (Figure 3a), which is responsible for the oxidation of the metals present in PCBs from an insoluble metallic form (M⁰) to a soluble form of metal (M⁺) [37,38]. In the case of cyanogenic bacteria, the bioleaching mechanism consists of the production of cyanide from glycine (Figure 3b), where cyanide combines with the metals present in PCBs [36,39].

![Printed circuit boards (PCBs): (a) Cell phone and (b) Computer.](image-url)

**Table 1. Metals present in the printed circuit boards (PCBs) of computers and cell phones.**

| Type of PCBs  | Cu  | Fe  | Pb  | Ni  | Al  | Pd  | Au  | Ag  | References         |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-------------------|
| Computers     | 20  | 7   | 1.5 | 1   | 5   | 0.011| 0.025| 0.100| [3,27]            |
| Cell Phones   | 25  | 5   | 0.8 | 0.5 | 1   | 0.221| 0.035| 0.134| [27,31,32]        |

Figure 1. Printed circuit boards (PCBs): (a) Cell phone and (b) Computer.
Leaching carried out by fungi is mainly based on the reaction of acidolysis and the complexation (Figure 3c) of metals by the excreted metabolites, such as organic acids and amino acids, as well as the bioaccumulation of metals by the mycelium [40–42]. Although the adsorption and bioaccumulation of metals has been widely reported for bacteria, archaea, and fungi, Xia et al. [43] recently reported that in the case of fungi, the metals mobilized from PCBs during the bioleaching process can bioaccumulate in the mycelium or can be adsorbed by extracellular polymeric substances (i.e., polysaccharides and proteins).

It is important to mention that most of the investigations on the recovery of metals from WEEE by microorganisms have been carried out with a combination of PCBs from different electronic equipment. Fewer are the reports that independently use the PCBs of computers and cell phones for their bioleaching experiments. The use of PCBs from a single electronic equipment could be important, since according to tests carried out with Aspergillus niger MXPE6, it has been observed that the recovery of Au is greater when using PCBs from cell phones and computers independently than by combining both types of PCBs (unpublished data). The popular use of PCBs from computers and cell phones in bioleaching tests is due to the fact that they are easier to obtain and manipulate in the laboratory, without the need of sophisticated tools for the dismantling of computers and cell phones, in comparison with other types of WEEE that require specific tools for dismantling (unpublished data).

As for the microorganisms used in the bioleaching of metals from the PCBs of computers and cell phones, it has been found that acidophilic and cyanogenic bacteria are not isolated from sites contaminated with WEEE; instead, they have another source. In contrast, there are reports mentioning...
the isolation of bacteria (i.e., *Pseudomonas*, *Bacillus*, *Clostridium*, *Rhodococcus*, and *Achromobacter*) and heterotrophic fungi (i.e., *Candida*, *Aspergillus*, *Fusarium* and *Trichoderma*) in sites contaminated with WEEE, which have then used in the recovery of metals from PCBs [13,44–47]. Another fact is that considering the experimental design, bacteria have been commonly used for the bioleaching of base metals from PCBs, while fungi for the bioleaching of precious metals [48].

Regarding the cited works in which bacteria are used for the bioleaching of metals from the PCBs of computers and cell phones (Table 2), different procedures have been used to increase the recovery of metals: (1) Modification of culture conditions, (2) addition of PCBs in different sizes and pulp densities (describing the mass of the PCBs in unit volume of liquid available, usually expressed as a% w/v), (3) addition of substances in the bioleaching process, (4) pretreatments for PCBs before bioleaching, and (5) physicochemical treatments after bioleaching.

Within the first procedure, modifications of the incubation time, temperature, amount of bacterial inoculum, pH, in addition to the use of consortia and the use of different carbon sources, have been reported [49–51]. In the particular case of acidophilic bacteria, different concentrations of iron, citric acid, and lemon juice have been tested [52–54], as well as the addition of metallic iron (Fe$^0$), ferrous sulfate [FeSO$_4$(H$_2$O)$_7$], and elemental sulfur (S$^0$) to the culture medium as an energy source [55]. The culture medium has even been renewed to restore the initial volume of the bioleaching process [56]. Some examples include the work of Priya et al. [54] which reported that the bioleaching of Cu (18%) and Ni (10%) from PCBs by *Acidiphilium acidophilum* increased with the addition of lemon juice and citric acid to the culture medium; the work of Willner and Formalczyk [50], which reported that bacterial inoculum concentrations greater than 20% increase the bioleaching of Cu by *Acidithiobacillus ferrooxidans*; the work of Shah et al. [51], which reported that the bioleaching of Cu, Zn, and Ni by *Leptospirillum ferriphilum* consortium increased by 25%, 21%, and 22%, respectively, by adding the PCBs to the culture medium after the complete oxidation of Fe$^{2+}$ to Fe$^{3+}$; the work of Choi et al. [52], which reported that at a concentration of 7 g·L$^{-1}$ of Fe$^{2+}$ ions there is greater Cu bioleaching and that at concentrations greater than 7 g·L$^{-1}$ of Fe$^{2+}$ ions, the Cu bioleaching decreases; and the work Garg et al. [55], which reported that Cu bioleaching was 100% when the culture medium was supplemented with metallic iron, while when the culture medium was supplemented with elemental sulfur, the Cu bioleaching was 40%.

In the second procedure, PCBs from computers and cell phones have been used in fragments (2 × 2 cm$^2$ to 12 × 6 cm$^2$) [57,58], powder (0.037–2.5 mm) [38,52,55–63], and pulp density (0.5–15% w/v) [64–70]. However, the use of a standard particle size for PCBs that improves the solubilization of metals by the action of bacteria has not been reported. In this sense, Wang et al. [53] reported that the percentages of Cu, Pb, and Zn solubilized in the bioleaching process carried out by the pure culture of *A. ferrooxidans*, the pure culture of *Acidithiobacillus thiooxidans*, and the mixed culture of *A. ferrooxidans* and *A. thiooxidans* increased when the particle size of the PCBs decreased. In contrast, Adhapure et al. [71] mentioned that the use of pulverized PCBs in the bioleaching process makes metal recovery difficult because the precipitate formed during bioleaching contaminates the pulverized PCB sample, and such mixing creates problems for the final separation of the non-metallic fraction from the PCB sample.

Meanwhile, in the third procedure, the addition of hydrogen peroxide to aid metallic oxidation [72] and the addition of graphite as a catalyst for the bioleaching process have been reported. Tong et al. [56] reported that the addition of graphite improved the solubilization of Cu from PCBs (4%) by the consortium (i.e., *A. ferrooxidans*, *Ferroplasma acidiphilum*, and *L. ferriphilum*). Chi et al. [49] reported that the bioleaching of Cu from PCBs by *Chromobacterium violaceum* increased by 14% with the addition of hydrogen peroxide at pH = 10, while in the case of Au there was an insignificant increase.
Figure 3. Bioleaching process. (a) Acidophilic bacteria: The mechanism of these bacteria to mobilize metals from PCBs is through the oxidation of ferrous iron to ferric iron (Equation (1)) as a strong oxidizing and the oxidation of elemental sulfur to produce sulfurous acid (Equation (3)). The bacterial-generated ferric iron can leach metal sulfides such as chalcocite (Cu₂S) (Equation (2)) or pyrite (FeS₂) (Equations (4) and (5)) in an acidic medium [55]. In the bioleaching processes, in order to extract metals from PCBs, ferrous iron sulfate, elemental sulfur, biogenic sulfur, and pyrite have been used as an energy source for bacteria [66]. (b) Cyanogenic bacteria: The pathway of the production of bacterial cyanide from glycine has three steps. In the first step, glycine is transformed into an unstable imine by the action of glycine oxidase; in step two, the unstable imine is transformed into a highly unstable nitrile by the action of the dehydrogenases associated with the respiratory system [38,73]; and in step three, the unstable nitrile is transformed into hydrocyanic acid (HCN) through a non-enzymatic step (Equation (6)). Metal cyanides composed of metal atoms and one or more cyanide ions are represented by the formula Aₙ[M(CN)ₓ]ₙ, where A is an alkali, alkaline earth, or heavy metal, and M is typically a transition metal. They are able to form a transition metal cyanide complex (Equation (7)), which may release cyanide ions via further dissociation (Equation (8)) [39]. (c) Filamentous fungi: Organic acids play an important role in accelerating the detachment of metals from the surface of the PCBs [42]. Bioleaching in which organic acids are involved is mainly based on the deprotonation (Equation (9)) reaction and the formation of metal complexes (Equation (10)) [40]. It is worth mentioning that the participation of citric acid, oxalic acid, malic acid, and gluconic acid has been frequently reported for this bioleaching process [42,74].

In the fourth procedure, it has been reported that from the pyrolysis of PCBs, a coal is obtained that is subsequently subjected to the bioleaching process [75], as well as the elimination of the plastic and polymeric parts of the PCBs using the shaking table method [76]. In addition, magnetic separation of the constituents of PCBs has been reported [57], as well as the reduction of the particles of PCBs with mechanical activation. Gu et al. [58] reported that pre-treatment of PCBs with mechanical activation increased the bioleaching of Cu (19%), Ni (21%), and Zn (20%) by A. ferrooxidans. De Andrade et al. [57] reported that the magnetic separation of PCBs is relevant in non-magnetic fractions, where the bioleaching of Cu by A. ferrooxidans increased by 8%.

In the fifth procedure, the use of chemical extractants and foams to obtain the metals from the bioleaching process has been reported. Akbari et al. [77] reported that Cu can be efficiently extracted (96%) from the bioleaching solution with LIX984N diluted in kerosene in two stages.
Zhou et al. [67] reported the extraction of gold from the bioleaching solution using a continuous foam fractionation, with a cetyl trimethyl ammonium bromide (CTAB) concentration of 0.2 g·L\(^{-1}\), a volumetric air flow of 100 mL min\(^{-1}\), and a feed flow of 10 mL min\(^{-1}\), resulting in the extraction of 73% Au. However, more research is needed in order to determine a high-efficiency bioleaching process, that includes several of the improvements already mentioned for the respective microorganisms.

Table 2. Prokaryotes used in the recovery of metals from printed circuit boards (PCBs) of computers and cell phones.

| Prokaryote (Bacteria or Archaea) | Prokaryote Type | PCBs Type | Recovered Metals * | Bioleaching Time | Bioleaching Type | Original Conditions | Optimized Conditions | References |
|---------------------------------|-----------------|------------|--------------------|------------------|------------------|---------------------|---------------------|-----------|
| Acidithiobacillus ferroxidans   | Acidophilic     | Computers  | 82% Cu, and 18% Cu | 6 days           | One-step         | Absence of ferrous ions in the culture medium. | Addition of iron (7 g·L\(^{-1}\)) | [52]      |
| Acidithiobacillus ferroxidans   | Acidophilic     | Computers  | 99% Cu             | 9 days           | One-step         | Two sieve fractions (1.0–3.0 and 0.5–1.0 mm). In a concentration range of PCBs from 0.7% to 1.9% v/v. | Decrease of the sieve fraction (0.5–1.0 mm) and decrease of the concentration of the PCBs (0.7% v/v). | [53]      |
| Acidithiobacillus thiooxidans   | Acidophilic     | Computers  | 79% Cu             | 9 days           | One-step         | Two sieve fractions (1.0–3.0 and 0.5–1.0 mm). In a concentration range of PCBs from 0.7% to 1.9% v/v. | Decrease of the sieve fraction (0.5–1.0 mm) and decrease of the concentration of the PCBs (0.7% v/v). | [53]      |
| Leptospirillum ferriphilum      | Acidophilic     | Computers  | 80% Cu, 76% Zn, and 71% Ni | 10–15 days       | One-step         | Sabouraud dextrose broth (SDB1) supplemented with 45 g·L\(^{-1}\) FeSO\(_4\)·7H\(_2\)O and PCBs (1 g). | SDB1 supplemented with 45 g·L\(^{-1}\) FeSO\(_4\)·7H\(_2\)O and simultaneous addition to the medium of the inoculum (10% v/v of activated inoculum) and PCBs (1 g). | [51]      |
| Leptospirillum ferriphilum      | Acidophilic     | Computers  | 85% Cu, 97% Zn, and 93% Ni | 6–8 days         | Two-step         | Biologically generated Fe\(^{3+}\) containing medium, free from cells and 1 g PCBs. | Addition of the PCBs to the culture medium after complete oxidation of Fe\(^{2+}\) to Fe\(^{3+}\). Biologically generated Fe\(^{3+}\) containing medium with viable inoculum and 1 g PCBs. | [51]      |
| Leptospirillum ferriphilum-dominated consortium | Acidophilic | Computers | 99% Cu | 10 days | One-step | Biologically generated in a continuous mode with a slurry flow rate of 10 L per day for 5 days (feeding stopped for the next 5 days to adapt the microorganisms, pulp density 1% v/v). | The bioleaching experiment carried out in a continuous mode with a slurry flow rate of 10 L per day for 5 days (feeding stopped for the next 5 days to adapt the microorganisms, pulp density 1% v/v). | [77]      |
| Leptospirillum ferriphilum-dominated consortium | Acidophilic | Computers | 99% Cu | 10 days | One-step | Biologically generated in a continuous mode with a slurry flow rate of 10 L per day for 5 days (feeding stopped for the next 5 days to adapt the microorganisms, pulp density 1% v/v). | The bioleaching experiment carried out in a continuous mode with a slurry flow rate of 10 L per day for 5 days (feeding stopped for the next 5 days to adapt the microorganisms, pulp density 1% v/v). | [77]      |
| Acidithiobacillus ferrooxidans  | Acidophilic     | Computers  | 95% Cu, and 75% Zn | 9 days           | One-step         | Initial conditions (30–50 °C, solid concentration of 5% w/v, and 10 g·L\(^{-1}\) of Fe\(^{2+}\)). | Optimization of culture conditions (30 °C, solid concentration of 5% w/v, bacterial inoculum, and 10 g·L\(^{-1}\) of Fe\(^{2+}\)). | [64]      |
| Acidiphilium acidophilum        | Acidophilic     | Computers  | 100% Cu            | 2.5 h            | Indirect bioleaching | Growth of the bacteria for 10 days in 1 L medium with glucose and salt. | Immersion of the PCBs in the culture medium in which the bacteria grew (without cells) + hydrogen peroxide (30%). | [73]      |
| Prokaryote (Bacteria or Archaea) | Prokaryote Type | PCBs Type | Recovered Metals * | Bioleaching Time | Bioleaching Type | Original Conditions | Optimized Conditions | References |
|---------------------------------|----------------|-----------|--------------------|------------------|------------------|--------------------|--------------------|-----------|
| **Consortium formed by Acidithiobacillus ferrooxidans, Ferroglocosma acidiphilum and Leptospirillum ferriphilum** | Acidophilic | Computers | 81% Cu | 5 days | One-step | No addition of graphite. | Addition of graphite (0.5 g). | [56] |
| **Acidithiobacillus ferrooxidans** | Acidophilic | Computers | 32% Cu | 7 days | One-step | Carried out in a range of inoculum concentrations (15, 35, and 35°C), pH 17 and 10, and different amino acids (glycine, methionine, and glycine + methionine). | Optimization of culture conditions (pH 2, graphite density 1%, and 45% in bacterial inoculum). | [55] |
| **Pseudomonas halocarica SAEI** | Cyanogenic | Computers | 74% Au, and 42% Ag | 7 days | Two-step | Initial conditions (5% v/v bacterial inoculum, and 30°C, without PCBs). | Optimization of culture conditions (pH 8.6, pulpdensity 0.5%, 6.8 g·L⁻¹ glycine, and 31.2°C). | [62] |
| **Acidithiobacillus ferrooxidans** | Acidophilic | Cell phones | 38% Cu, 11% Au, and 12% Ag | 8 days | One-step | Carried out with different temperatures (15, 25, and 35°C), pH 7 and 10, and different amino acids (glycine, methionine, and glycine + methionine). | Optimization of culture conditions (pH 9, pulpdensity 0.5%, 6.8 g·L⁻¹ glycine, and 31.2°C). | [78] |
| **Chromobacterium violaceum** | Cyanogenic | Cell phones | 100% Cu and 100% Ni | 21 days | One-step | Bacteria inoculated into 9 K medium at volumedoses of 10%, 20%, 50%, and 100% (v/v) at 20–22°C and pH 2.5. | The highest recovery of copper obtained with 100% dose. | [56] |
| **Leptospirillum ferriphilum-dominated consortium** | Acidophilic | Cell phones | 100% Cu, 99% Zn, and 85% Ni | 6-8 days | Two-step | Biologically generated Fe³⁺ iron (0.80%) containing medium, free from cells and 1 g PCBs. | Addition of the PCBs to the culture medium after complete oxidation of Fe³⁺ to Fe⁴⁺. | [51] |
| **Leptospirillum ferriphilum** | Acidophilic | Cell phones | 94% Cu, 91% Ni, 91% Zn, 10% Pb, 75% Co, and 54% Cd | 9 days | One-step | Carried out with different concentrations of glycine (0.5, 2.4, 5.3, 8, 10 g·L⁻¹), different pH level (7, 7.6, 8.5, 9.6, and 10), and different pulpdensities (2, 5.7, 8.1, 16.4, and 20 g·L⁻¹). | Optimization of culture conditions (pH 10, 10 g·L⁻¹ glycine, and pulpdensity 0.8%). | [60] |
| **Acidithiobacillus ferrooxidans** | Acidophilic | Cell phones | 100% Cu, and 100% Ni | 24 days | One-step | Bacteria inoculated into 9 K medium at volumedoses of 10%, 20%, 50%, and 100% (v/v) at 20–22°C and pH 2.5. | The highest recovery of copper obtained with 100% dose. | [56] |
| **Pseudomonas balearica** | Cyanogenic | Computers | 74% Au, and 42% Ag | 7 days | Two-step | Initial conditions (5% v/v bacterial inoculum, and 30°C, without PCBs). | Optimization of culture conditions (pH 8.6, pulpdensity 0.5%, 6.8 g·L⁻¹ glycine, and 31.2°C). | [62] |
| **Pseudomonas chlororaphis** | Cyanogenic | Cell phones | 52% Cu, 8% Au, and 12% Ag | 4 days | One-step | Carried out in a range of inoculum concentrations (10–40% w/v), pH level (1.6–2.4), and pulpdensities (1–4% v/v). | Optimization of culture conditions (pH 2, graphite density 1%, and 45% in bacterial inoculum). | [55] |
| **Bacillus megaterium** | Cyanogenic | Cell phones | 72% Cu, and 3% Au | 9 days | One-step | Carried out with different concentrations of glycine (0.5, 2.4, 5.3, 8, and 10 g·L⁻¹), different pH level (7, 7.6, 8.5, 9.6, and 10), and different pulpdensities (2, 5.7, 8.1, 16.4, and 20 g·L⁻¹). | Optimization of culture conditions (pH 10, 10 g·L⁻¹ glycine, and pulpdensity 0.8%). | [60] |
| **Leptospirillum sp.** | Acidophilic | Cell phones | 100% Cu | 6-8 days | Two-step | Carried out with different concentrations of glycine (0.5, 2.4, 5.3, 8, and 10 g·L⁻¹), different pH level (7, 7.6, 8.5, 9.6, and 10), and different pulpdensities (2, 5.7, 8.1, 16.4, and 20 g·L⁻¹). | Optimization of culture conditions (pH 10, 10 g·L⁻¹ glycine, and pulpdensity 0.8%). | [60] |
Table 2. Cont.

| Prokaryote (Bacteria or Archaea) | Prokaryote Type | PCBs Type | Recovered Metals * | Bioleaching Time | Bioleaching Type | Original Conditions | Optimized Conditions | References |
|---------------------------------|-----------------|-----------|-------------------|-----------------|-----------------|--------------------|--------------------|-----------|
| **Consortium formed by Acidithiobacillus ferrooxidans, Leptospirillum ferrophilum, Acidithiobacillus caldus, Acidithiobacillus thiooxidans, Sulphobacillus sp. and Ferroplasma sp.** | Acidophilic | Cell phones | 98–99% Cu | 12 days | One-step | Carried out with different pulp densities (7%, 10%, and 15% w/v). | Optimization of culture conditions, (pulp density 7%, 10%, and 15% w/v). | [60] |
| **Acidiphilium acidophilum** | Acidophilic | Cell phones | 2.4 mg Cu L⁻¹, and 1.3 mg Zn L⁻¹ | 15 days | One-step | Without adding lemon juice and citric acid. | Addition of lemon juice and citric acid. | [54] |
| **Acidithiobacillus ferrooxidans** | Acidophilic | Cell phones | 95–100% Cu | 2 days | Two-step | Biologically generated Fe³⁺ iron containing medium, free from cells and 2625 g PCBs. | Biologically generated Fe³⁺ iron containing medium with viable inoculum and 2625 g PCBs. | [38] |
| **Pseudomonas putida and Bacillus megaterium** | Cyanogenic | Cell phones | 84% Au | 34 h | One-step | Nm | Optimization of culture conditions (pH 10, and pulp density 0.5% w/v). | [67] |
| **Pseudomonas aeruginosa B3** | Cyanogenic | Cell phones | 57% Cu, 4% Zn, and 5% Ni | 8–10 days | One-step | Nm | Optimization of culture conditions (adapted bacterial cultures, and pulp density 0.5% w/v). | [70] |
| **Acidithiobacillus ferrooxidans** | Acidophilic | Mix of PCBs of computers and cell phones | 94% Cu | 10 days | One-step | Carried out with different pulp densities (0.5%, 1%, 2.5%, 5% w/v). | Optimization of culture conditions (pH 1.0–4.6, and pulp density 1% w/v). | [66] |
| **Acidithiobacillus thiooxidans** | Acidophilic | Mix of PCBs of computers and cell phones | 89% Cu | 10 days | One-step | Carried out with different pulp densities (0.5%, 1%, 2.5%, 5% w/v) and different concentrations of glucose (3.7%, 10 g L⁻¹). | Optimization of culture conditions (pH 1.0–4.6, and pulp density 1% w/v). | [66] |
| **Pseudomonas putida** | Cyanogenic | Mix of PCBs of computers and cell phones | 44% Au | 2 days | Two-step | Carried out with different pulp densities (0.5%, 1%, 2.5%, 5% w/v) and different concentrations of glucose (3.7%, 10 g L⁻¹). | Optimization of culture conditions (pH 1.0–4.6, and pulp density 1% w/v). | [66] |

Nm = Not mentioned. * Recovery percentage of metals in relation to the initial concentration of the metals in the leaching substrate.

There are less studies that report the use of fungi for the recovery of metals from electronic waste than for bacteria. The first studies reported the ability of Aspergillus niger and Penicillium simplicissimum to recover Cu, Sn, Al, Ni, Pb, and Zn from WEEE dust [80]. It is worth mentioning that these fungal genera have also been used for the recovery of metals from the PCBs of computers and cell phones, and that in recent years others fungal genera have been tested as shown in Table 3. To increase the recovery of metals in the bioleaching process, two procedures have been used: (1) Modification of culture conditions, and (2) addition of PCBs in different sizes and pulp densities. Regarding the first procedure, agitated and stationary cultures, inoculation of fungi with mycelium (agar discs with cut mycelium) or spores have been used, as well as the use of fungal consortia [44–46,81,82]. In addition, other carbon sources such as cheese whey, sugar, and sugar cane molasses have been used. Some examples include the works of Argumedo et al. [45], Trivedi et al. [82], and Arshadi et al. [81]. Argumedo et al. [45] reported that the use of the A. niger consortium increased the bioleaching of Au from PCBs by 39%. In contrast, Trivedi et al. [82] reported that the use of the Aspergillus consortium had a marginal increase in the bioleaching of Cu (5%) and Ni (4%) from PCBs. Another important improvement is the use of other carbon sources, for which Arshadi et al. [81] reported that the bioleaching of Cu (90%) from PCBs by P. simplicissimum increased when sugar was used as a carbon source, while that of Ni (89%) increased when using molasses as a carbon source; in addition, a copper bioleaching of 77% for sucrose and 65% for cheese whey was reported when used as a carbon source for the fungus.
Table 3. Fungi used in the recovery of metals from PCBs of computers and cell phones.

| Fungus                          | Fungus Type | PCBs Type | Recovered Metals * | Bioleaching Time | Bioleaching Type | Bioleaching Conditions                                                                 | References |
|---------------------------------|-------------|-----------|--------------------|------------------|------------------|----------------------------------------------------------------------------------------|------------|
| Trichoderma viride              | Filamentous | Computers | 1% Pd, and 10% Au  | 30 days          | One-step         | pH 5, 1 g PCBs of 0.5 x 0.5 cm², and inoculation with mycelium.                         | [83]       |
| Trichoderma atroviride          | Filamentous | Computers | 1% Pd, and 13% Au  | 30 days          | One-step         | pH 5, 1 g PCBs of 0.5 x 0.5 cm², and inoculation with mycelium.                         | [83]       |
| Aspergillus tubingensis         | Filamentous | Computers | 34% Cu, 54% Zn, and 8% Ni | 33 days | One-step | pH 5, pulp density 0.25-1% w/v, and inoculation with spores.                        | [74]       |
| Aspergillus niger               | Filamentous | Computers | 7% Cu, 32% Ni, and 79% Zn | 33 days | One-step | Pulp density 0.1% w/v, and inoculation with spores.                             | [82]       |
| Consortium formed by Aspergillus niger and Aspergillus tubingensis | Filamentous | Computers | 76% Cu, 36% Ni, and 63% Zn | 33 days | One-step | Pulp density 0.1% w/v, and inoculation with spores.                             | [82]       |
| Aspergillus niger MXPE6         | Filamentous | Cell phones | 5% Cu, 42% Au, and 0.8% Ni | 14 days | One-step | pH 4.4, and 0.2 g PCBs of 1 x 1 cm².                                         | [44]       |
| Consortium formed by Aspergillus niger MXPE6 and Aspergillus niger MX7 | Filamentous | Cell phones | 56% Au,                | 16 days | One-step | pH 5, 11 g PCBs of 0.0994 mm, 5 L bioreactors in batch mode, and inoculation with mycelium. | [45]       |
| Aspergillus niger MXPE6         | Filamentous | Cell phones | 54% Ag                | 35 days | One-step | pH 4.4, 11 g PCBs of 0.594 mm, and 5 L bioreactors in batch mode.                  | [45]       |
| Aspergillus niger MX5           | Filamentous | Cell phones | 3% Cu, and 0.3% Au    | 35 days | One-step | pH 4.4, 0.5 g PCBs of 0.994 mm, and inoculation with mycelium.                     | [45]       |
| Aspergillus niger MX7           | Filamentous | Cell phones | 0.5% Cu, and 0.5% Au  | 35 days | One-step | pH 4.4, 0.5 g PCBs of 0.994 mm, and inoculation with mycelium.                     | [45]       |
| Candida orthopsilosis           | Yeast       | Cell phones | 1% Cu                 | 35 days | One-step | pH 4.4, 0.5 g PCBs of 0.994 mm, and inoculation with mycelium.                     | [45]       |
| Penicillium simplicissimum      | Filamentous | Cell phones | 90% Cu, and 89% Ni    | Nm               | One-step | Four kinds of carbon sources (i.e., sucrose, cheese whey, sugar, and sugar cane molasses). | [81]       |

Nm = Not mentioned. * Recovery percentage of metals in relation to the initial concentration of the metals in the leaching substrate.
Meanwhile in the second procedure the use of PCBs from computers and cell phones has been reported in fragments (0.5 × 0.5 cm² to 1 × 1 cm²) [44,83], powder (0.038–1 mm) [46,74,81,82,84] and pulp density (1–5% w/v) [43,81]. It is worth mentioning that particles of PCBs smaller than 0.0706 mm have been shown to inhibit the growth of fungi such as *Aspergillus niger*, *Trichoderma harzianum*, *T. viride*, *Fusarium oxysporum*, and *F. solani* [45]. Despite all of the above-mentioned improvements, there is still a disadvantage in that the fungus bioleaching process requires more time than that of bacteria, which is why it is necessary to improve the metal recovery efficiency to compensate for this disadvantage.

### 4. Plants in the Recovery of Metals from Printed Circuit Boards of Computers and Cell Phones

The first reports of the interaction of plants with metals derived from electronic waste were that of Peng et al. [85] and Tang et al. [86]. They reported that crops near the places where electronic waste is recycled (Taizhou, China) have high concentrations of metals, such is the case of rice with a high concentration of Hg. The ability of plants to accumulate metals in their tissues (the aerial part and roots) has been widely reported, and this mechanism is taken as the basis for phytoremediation and phytomining processes [87,88]. Among the mechanisms of the interaction of plants with metals are phytoextraction, phytostabilization, and phytovolatilization [89]. Based on the mechanisms mentioned above, the study of Díaz-Martínez et al. [90] was one of the first to report the use of plants to recover metals from electronic waste in an in vitro system. In this investigation, *Lolium perenne* L. and *Medicago sativa* L. were tested to phytoextract Pb from the PCBs of computers. Other studies where plants were used to extract metals from the PCBs of computers and cell phones are shown in Table 4. The plants were cultivated in sand and hydroponic cultures, taking care that the plants were not affected in their growth by the presence of the PCBs.

It is important to mention that solid substrates such as soil, sand, vermiculite, or perlite have the advantage of being closer to natural edaphic conditions; their heat capacity, matrix potential, and ion exchange capacity buffer the rhizosphere from rapid changes in temperature, water availability, and nutrient concentrations [91]. However, these substrates present a complex medium that is not susceptible to standardization or direct observation, for example, the separation of the roots from the sand is stressful, not only for the roots, but also for the researcher. To avoid such difficulties, hydroponic cultures have been used, which have the advantage of greater efficiency in the use of nutrients and water [92]. It has been observed that the recovery of metals from PCBs by plants grown in sand is less than that of plants grown in hydroponic systems. Therefore, hydroponic crops typically chosen as they also facilitate the operation of the metal recovery process.

Díaz-Martínez [83] mentioned that the toxicity of PCBs in plants depends on the nutrient solution used, the genotype of the plant, and the amount of PCBs, which is of great importance for improving the phytoextraction of the metals present in the PCBs of computers and cell phones. In those studies consulted that were, it was observed that most plants accumulate metals in their roots, due to the design of the experiments, since the roots have direct contact with the PCBs of computers and cell phones (Figure 4).

The phytoextraction of metals can be improved with the help of plant growth promoting bacteria, where these bacteria transform metals into bioavailable and soluble forms through the action of siderophores, organic acids, biosurfactants, biomethylation, and redox processes [93]. A strategy to increase the phytoextraction of metals from PCBs is the inoculation of bacteria, taking into account studies in which an increase in the extraction of metals was reported due to the inoculation of bacteria promoting plant growth [94], such is the case of *Sphingomonas SaMR12* that when inoculated in *Sedum alfredii* improves the extraction of cadmium by the plant [95]. Another example is the inoculation of *Sphingomonas* sp. SaMR12 and *Enterobacter* sp. SaCS20 in the plants of Japonica rice (*Oryza sativa* L.) variety Nipponbare. Under hydroponic conditions, inoculation of SaMR12 and SaCS20 bacteria increased the concentration of Zn by 44.4% and 51.1% in the shoots and by 73.6% and 83.4% in the roots, respectively [96]. Considering the above, Díaz-Domínguez et al. [97] reported that *Medicago sativa* with and without inoculation of *Pseudomonas tolassi* does not show significant differences
in the phytoextraction of Cu from computer PCBs. However, in this sense there is still an immense field of research that could find in the future, a positive plant-microorganism interaction that could increase the phytoextraction of metals from the PCBs of computers and cell phones.

![Diagram of phytoextraction system](image)

**Figure 4.** Accumulation of Cu, Au, and Pd from the PCBs of computers and cell phones in the roots of plants grown in a hydroponic system and in a sand system.

**Table 4.** Plants used in the recovery of metals from PCB of computers and cell phones.

| Plant          | System Type | PCBs Type | Recovered Metals          | Growing Time in the Greenhouse | Mechanism  | References |
|----------------|-------------|-----------|---------------------------|-------------------------------|------------|------------|
| *Medicago sativa* L. | Sand        | Computers | 2% Pd, and 0.01% Cu       | 20 days                       | Phytoextraction | [98]       |
| *Lolium perenne* L. | Sand        | Computers | 0.08% Pd, and 0.2% Cu     | 20 days                       | Phytoextraction | [98]       |
| *Triticum* sp.        | Hydroponic  | Computers | 25% Au                    | 20 days                       | Phytoextraction | [99]       |
| *Sinapis alba* L.     | Hydroponic  | Cell phones | 6% Cu, 0.7% Au, and 3% Pd | 20 days                       | Phytoextraction | [99]       |
| *Helianthus annuus* L. | Hydroponic  | Cell phones | 7% Cu, 0.6% Au, and 5% Pd | 20 days                       | Phytoextraction | [99]       |
| *Lens culinaris*      | Hydroponic  | Cell phones | 46% Au, and 47% Pd        | 30 days                       | Phytoextraction | [100]      |

5. Prospects and Recommendations for the Bio-Recovery of Metals from the PCBs of Computers and Cell Phones

Considering the disadvantages of hydrometallurgical and pyrometallurgical processes, bio-recovery processes (i.e., using microorganisms and plants) have been proposed as a sustainable alternative. However, they still face several disadvantages and challenges, which are herein discussed according to the point of view of various authors and the authors of this review.
Based on an extensive review of the literature and in subsequent follow up discussions/interviews with approximately 20 leading experts in the bio-recovery of metals from PCBs, the consensus of the authors is that bio-recovery of the PCBs from computers and cell phones is a more promising approach than recovery via hydrometallurgical and pyrometallurgical methods due to their less adverse environmental impact [8,10,22,23,101–104]. In addition, bio-recovery processes have other advantages, such as being able to work at ambient temperatures and pressures, being economically profitable, requiring lower energy inputs, and generating minimal secondary waste [8,101]. However, there are several challenges to having a standard green technique available for the recovery of metals from the PCBs of computers and cell phones, including: (1) Carrying out further studies on the techniques of physical separation of the constituents of PCBs, particularly the separation of hazardous components from non-hazardous materials (which is a crucial step in the minimization of toxicity concerns during processing) [23]; (2) improving the understanding of the bioleaching, biosorption, and biomineralization mechanisms that could lead to more precise technologies, thereby increasing their efficiency and selectivity (the combination of these technologies has emerged as a promising application in biorecovery processes) [103]; (3) reducing the time of the bioleaching process (so that the process can be viable) [23,104]; (4) using profitable substrates where microorganisms can grow properly so that the efficiency of the recovery of metals from PCBs is increased (i.e., substrates that allow directing the metabolic pathway toward the production of substances that improve the bioleaching of metals) [15]; (5) carrying out further studies on the methods of separation and purification of the metals present in the final bioleaching, combining physicochemical and biological methods (i.e., hybrid technologies) [21,105], which could be economically viable if the appropriate combination of biological and chemical processes is found, as mentioned by Pant et al. [32]; (6) increasing the use of microbial consortia (for the recovery of precious metals) [103]; (7) exploring the mechanism of the intracellular resistance of fungi exposed to metals contained in the PCBs of computers and cell phones (in order to find highly metal-resistant fungi that can increase the efficiency of metal recovery) [8]; (8) in the case of acidophilic bacteria, avoiding the release of the acid produced during the bioleaching process to local bodies of water [104]; (9) developing genetically modified microorganisms to increase the bioleaching of metals (which can alleviate the metal toxicity during the PCB bioleaching process) [15]; (10) making use of genomic, proteomic, transcriptomic, and metabolomic tools to detect and isolate the genes that encode biomolecules (i.e., DNA, lipids, enzymes and polymeric substances) that are useful in the processes of bioleaching, bioreduction, bioaccumulation, biosorption, bioprecipitation, bioreduction, biooxidation, and biomobilization [48,106]; (11) using the electrolysis process as a tool to obtain high purity metals from bioleaching [48]; (12) carrying out pilot-scale experiments, leading to the optimization of the process design and the overall performance of metal recovery prior to large-scale implementation [84]; (13) optimizing the operating parameters and improving the automatic operation and monitoring of metal recovery technology [105]; (14) seeking to use the metals obtained from the PCBs of computers and cell phones in the manufacturing of new electronic products and in the production of nanometals [22,84,107,108].

The following suggestions are proposed to improve the bio-recovery of metals from the PCBs in computers and cell phones:

5.1. Microorganisms

(1) Carry out further testing using metal-tolerant microbial populations with diversity should continue, as metal tolerance assays have been shown to be useful in screening for microorganisms with the potential to recover metals from PCBs [44]. In addition, so far there are reports on eight bacterial genera (i.e., Acidithiobacillus, Leptospirillum, Sulfobacillus, Ferroplasma, Acidiphilium, Leptospirillum, Chromobacterium, Pseudomonas, and Bacillus) and four fungal genera (i.e., Aspergillus, Penicillium, Candida, and Trichoderma), while in the case of microalgae no reports have been found.
(2) Continue exploring the culture of fungi under stationary conditions to decrease energy expenditure, since some fungi have been reported to result in higher metal recovery in stationary systems than in agitated systems [45].

(3) Determine the toxicity of the particle size and the concentration of the pulp of the PCBs in the microorganisms that are used for the bioleaching process, since the growth of some fungi has been reported to be inhibited when particles from PCBs smaller than 0.0706 mm are used [48]. Likewise, determining the technical difficulty of handling powder, pulp, or fragments in the bioleaching process is important, since it has been reported that using powder in the bioleaching process hinders the general metal recovery process [71].

(4) Study in more detail the waste generated by microbial processes, as it could be reused. For example, the microbial biomass obtained from the bioleaching process could be used to extract lipids and to test their potential in the production of microbial biodiesel.

(5) Carry out studies on the energy consumption of biological processes for the recovery of metals from PCBs in order, to establish their industrial viability.

5.2. Plants

(1) Reports in the literature on plant genera capable of tolerating high concentrations of metals show that further testing is possible with the wide diversity of metal-tolerant plant species, since so far, very few genera of plants have been reported (i.e., Medicago, Lolium, Sinapis, Helianthus, Triticum, and Lens) in the recovery of metals from the PCBs of computers and cell phones.

(2) Continue testing the positive plant-microorganism association (using microorganisms that promote plant growth) to increase the recovery of metals from the PCBs of computers and cell phones.

(3) Use hydroponic systems instead of systems with solid substrates (which are technically complicated).

(4) Look for nutrient solutions that improve the growth and metal recovery of plants in contact with PCBs.

The recovery of metals from PCBs by biological methods has advanced considerably in recent years, and significant improvements have been made in bioleaching processes that have increased metallic recovery primarily in the case of acidophilic and cyanogenic bacteria, and to a lesser extent in the case of fungi. Meanwhile, for plants it is still unknown if this biotechnology could be viable. Considering the application of the bio-recovery processes of metals from PCBs by acidophilic and cyanogenic bacteria, it is still necessary to develop techniques for the treatment of generated waste. Consequently, the information reported in the literature to date is of great value since a high amount of WEEE is produced worldwide that causes high levels of pollution. Therefore, it is necessary to use existing information to continue searching for and developing environmentally friendly and low-cost alternatives for the recovery of metals from the PCBs of computers and cell phones so as to meet the demand for metals without continuing to destroy entire ecosystems by mining.

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