

# Biorecovery of Precious Metal Nanoparticles From Waste Electrical and Electronic Equipments

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## 1 The Problem of Waste Electrical and Electronic Equipment (WEEE): An Overview

The term waste electrical and electronic equipment (WEEE) or E-waste is defined as electrical and electronic equipment (EEE) that is at the end of its life or that has been discarded as waste without the intent of re-use. WEEE has become a serious problem throughout the world due to an increasing trend of accumulation and nil or low rates of degradability by natural means. The major reasons behind generating higher amounts of WEEE are the shortened life spans of new electronic equipment compared to the past (Babu et al., 2007) and changing consumption patterns of electrical and electronic items. Accordingly, the per capita WEEE generation ranges from 1.7 to 15.6 kg/person depending on the country, irrespective of the size of the population, but the highest amounts are from the economically advanced American and European regions. The global annual generation of E-waste was estimated to be 6.1 kg per inhabitant per annum in 2016, and this is expected to reach 52.2 million metric tons (Mt), or 6.8 kg/inhabitant, by 2021 (Baldé et al., 2017).

Attempts to find mitigation measures to overcome the WEEE problem started in the early 1990s with the Basal Convention. With the introduction of new technologies such as green electronics (Irimia-Vladu, 2014) preexisted technologies were replaced. Recycling of WEEE has been recognized as a

major solution to the associated waste problem and scientists have been keen to invent on sustainable and green recycling technologies. Recycling of WEEE by conventional chemical and physical methods was challenging because of high energy consumption, low cost effectiveness due to high labor and time consumed, and generation of secondary pollutants. Consequently, industry and researchers have continued to engage in the process of inventing new means of recycling as their economic gains were higher. Additional to economic gains, recycling of WEEE has the advantage of protecting the environment from contamination that threatens human life.

The chemical composition of WEEE is not consistent and also changes with the advent of new technology. However, in general, WEEE can be categorized into two major groups: metallic and nonmetallic. Precious metals such as Ag, Au, and Pt group metals (Pt and Pd), and other metals such as Al, Cu, Cr, Ni, Sb, Sn, Zn, Pb, Hg, Cd, and Fe are the major metal elements that can be found in WEEE. Amongst these, Pb, Hg, Cd, and Cr can cause serious toxic effects to the environment. Additionally, polybrominated diphenyl ethers (PBDEs) including flame retardants, polychlorinated biphenyls (PCBs), phosphorus (P), hexavalent chromium and ozone-depleting substances are the main nonmetallic constituents found in WEEE material (Robinson, 2009; Baldé et al., 2015; Kaya, 2016; Işildar et al., 2016).

Scarcity and high economic values fetched by precious metals have favored the invention of more cost-effective and environmentally sound methods for recovery. WEEE can generate precious metals with high quality and more yield than when recovered from natural ores (Tay et al., 2013). E-waste contains more Au (1–1000 g/Au/ton/WEEE) than can be found in ores (0.5–13.5 g Au/ton Au ore) (Natarajan et al., 2015), therefore reducing the demand for natural ores.

## 2 Bioleaching as a Strategy to Extract Metals and Metal Nanoparticles

### 2.1 History of Bioleaching

Bioleaching is the process of extracting metals from waste using biological systems such as microbes and plants. The history of bioleaching goes as far back as BCE in Europe and Asia and suggests that people had been unknowingly practicing the mechanisms of the microorganisms that are involved. The Roman writer, Gaius Plinius Secundus (23–79 AD) wrote about a Cu leaching process. This is one of the earliest reports on bioleaching using remnants of decomposed minerals. Another report is that Georgius Agricola (1494–1555), in Germany, depicted the manual Cu leaching process using leachates from mines. However, presently, the Rio Tinto mines in southwestern Spain are considered the location of the foundation of biohydrometallurgy. In addition to Cu, these mines have been utilized since the pre-Roman era for extraction of precious metals such

as Au and Ag. The involvement of metal ions in oxidizing bacteria with *Thiobacillus* was discovered from ore leachates (Ehrlich, 2004; Mishra et al., 2005).

## 2.2 Extraction of Metals and Metal Nanoparticles: Green Methods Versus Conventional Means

Microbes possess the ability to recover precious metals from low-grade ores under marginal metal concentrations. Au biomining has achieved higher success compared to other high-value metals (Bharadwaj and Ting, 2012). Some conventional hydrometallurgical processes such as Au extraction use higher amounts of  $CN^-$  which in turn can exert toxic effects into the environment. The release of  $CO_2$  is low during the process of bioleaching.

Nanomaterials that possess one or more dimensions in the range of 1–100 nm have attracted great attention due to their fascinating properties, and advantageous applications. Both the top-down strategy and bottom-up strategy are used to generate nanoparticles (NPs). In the case of a top-down strategy, the materials are used in their bulk form and then reduced to nanosize, while in the bottom-up strategy, the nanostructure formation occurs atom by atom, molecule by molecule, or through self-organization (Zielonka and Klimek-Ochab, 2017). The synthesis by biological or green means follow the bottom-up approach.

Green synthesis of NPs has gained attention for a variety of reasons. Such methods incur relatively low costs and can easily be scaled up (Keat et al., 2015). Microorganism-mediated synthesis of NPs has been identified as one of the green methods available for producing NPs. In this process the microorganisms include fungi, bacteria, actinomycetes, and viruses. The reasons for using microbial-mediated NP synthesis mechanisms are due to the disadvantages of the physical and chemical means of synthesis that result in the generation of various harmful chemicals, and are relatively ineffective in terms of financial and energy costs. The various chemical and physical methods include radiation, chemical precipitation, and photo/electrochemical methods. Moreover, the physical and chemical methods do not always yield higher output of NPs and are usually associated with low production rate while causing various types of deformations in the particles and inhibition of particle growth (Keat et al., 2015).

Sometimes the NPs produced using chemical methods possess low stability, and sometimes it cause difficulties in controlling the crystallization and aggregation of resulting NPs (Roy et al., 2016). Furthermore, they may possess comparatively higher toxicity than green-synthesized ones. However, biological system-mediated NPs are the least toxic due to association with capping agents or surfactants, and have a higher solubility and biocompatibility (Schröfel et al., 2014). In the various microbial categories, much attention has been gained by fungi and bacterial synthesis rather than using other microorganisms due to technological advancements. Despite the number of advantages mentioned

above, it may incur issues when purifying due to contamination with biological matter or molecules which may need to be removed (Schröfel et al., 2014). Moreover, there is a potential risk of killing bacterial cells due to the higher toxicity of constituents such as the toxic metals of the mixture. Having low a low lixiviant concentrations can extend leaching time (Natarajan and Ting, 2015), and these two risks are common to any bioleaching process.

### 2.2.1 Preparation of WEEE Materials for Metal Extraction

Recycling of WEEE involves three steps (Kaya, 2016): pretreatment, separation, and refining and purification. Pretreatment includes manual or automatic disassembly of the various components of the E-waste. During the separation process, shredding, crushing, pulverizing, and then screening are practiced using cutters such as rotary cutting shredders and then ground to micro-sized particles using ultracentrifuge mills. According to the literature, the final particle sizes suitable for the reactions range between 100 and 500  $\mu\text{m}$  (Ilyas and Lee, 2014; Işıldar et al., 2016; Natarajan et al., 2015). Furthermore, researchers have practiced the sterilization of crushed matter. This prevents the growth of unwanted microorganisms during the reaction process. For instance, Işıldar et al. (2016) practiced tyndalization. The resulting E-waste powder is treated with acids for digestion followed by addition of microorganisms while maintaining the pulp density and incubated under shaking conditions. The resultant NPs are analyzed for their composition using various techniques.

### 2.2.2 Bioleaching of Metals by Microorganisms: Cellular Mechanisms Involved

The synthesis of NPs occurs either extracellularly or intracellularly with the involvement of a number of biochemical reactions associated with the cellular environment. These processes are often associated with various mechanisms mediated by the proteins such as enzymes. These proteins might play multiple roles such as reduction, controlling size and shape, in addition to reducing the metal ions into a nanosize. Whether the production of NPs occurs either by extracellular or intracellular environments is dependent upon the growth conditions of the microorganism culture. For an example, *Trichothecium* spp. at its stationary phase has formed Au NPs extracellularly, however, under shaking environment, was produced the same intracellularly. This might be attributed to the release of certain enzymatic polypeptides responsible for the formation of NPs under stationary conditions but are not released under shaking conditions.

The synthesis of NPs by intracellular means includes a special ion transportation mechanism inside the cells. In such situations and the cell walls play a vital role. The intracellular synthesis involves three steps: trapping, bioreduction, and capping. Trapping occurs when the metal ions attach to the cell surfaces and attachment is facilitated by electrostatic interactions. The metal ions are then reduced to nano form through enzymatic reactions. The extracellular

synthesis of NPs using microbes is mediated by enzymes (reductases) that aid in reducing the metallic ions into their reduced forms. Many studies have claimed the involvement of nitrate reductase and nicotinamide adenine dinucleotide plus hydrogen (NADH)-dependent reductase in reducing metal ions into NPs (Hulkoti and Taranath, 2014).

### 3 Suitable Conditions for Bioleaching With WEEE and Their Proven Success

Metals in WEEE are present in their typical stable form and or as alloys. Optimum oxidative leaching conditions should therefore be maintained for efficient extraction of precious metals. Nonetheless selecting the suitable oxidizing agent (iron) is an important aspect in bioleaching processes. At the same time it is necessary to maintain the required pH of the mixture. Furthermore, the initial population size of the microorganisms also affects the efficiency of the process (Bas et al., 2013).

The use of mutated or genetically-modified strains in bioleaching is of great interest and has gained promising results. In any case, the dissolved oxygen level of the mixture is a critical factor that determine the final yield of the metal concerned. In some processes, an increase of dissolved oxygen in the reaction media has been experimented and proved to be effective in increasing the recovery of Cu and Au with *Chromobacterium violaceum*, which is a mesophilic, Gram-negative, facultative anaerobe that can solubilize Au as dicyanoaurate ( $\text{Au}(\text{CN})_2$ ) (Madrigal-Arias et al., 2015). The bacteria produce  $\text{CN}^-$  as a secondary metabolite that facilitates the extraction of Au and Cu. In a study, the researchers were able to increase the Cu and Au recovery from 11.4% to 24.6% and 10.8% to 11.31% respectively in printed circuit boards from mobile phones (Chi et al., 2011). It has been shown that the presence of higher amounts of Cu interferes with, and thus reduces, the cyanidation process of Au. Therefore, pretreatment of the scrap matter with nitric acid facilitate removing the Cu and other metals to enhance the Au cyanidation through increased  $\text{CN}^-$  production (Natarajan and Ting, 2014). Furthermore, they showed that pretreatment of the electronic scrap material prior to performing reactions also increased the efficiency of the Au biorecovery process. Interestingly they indicated that higher pulp densities decrease the cyanide production by the bacteria due to toxicity. The toxicity can occur due to the activity of Pd, Cd, Hg, and Cr (VI) which are typically present in E-waste (Madrigal-Arias et al., 2015). In another study, *C. violaceum*, *Pseudomonas aeruginosa*, and *P. fluorescens* were used to extract Au from electronic scrap material. Again, the pure culture of *C. violaceum* showed the highest  $\text{CN}^-$  production, followed by the Au recovery. Furthermore, a spent medium leaching showed higher Au recovery than two-step leaching while a higher pH of spent medium increased the  $\text{CN}^-$  availability for Au complexation. *P. aeruginosa* and *P. fluorescens* could recover up to half of the yield relative to *C. violaceum* (5.3%–5.8%). However, mixed cultures

achieved considerably higher rates of recovery (Natarajan and Ting, 2015). Higher bioleaching of Au was achieved from PCBs and gold-plated finger integrated circuits (GFICM) using *Aspergillus niger* and the recovery was ranged from 42% to 1% with different individual strains, but with a combination of two strains, this rate was enhanced up to 87% and 28% respectively for PCBs and GFICM (Madrigal-Arias et al., 2015).

The control of shape and size of synthesized NPs is a major challenge in microorganism-mediated synthesis. Furthermore, it does not ensure the production of the NPs. Therefore, the intermediary compounds may need to be further treated with a different strain of bacteria to obtain the desired NP species. For example, the gold bioaccumulation-enhancing cyanobacterial species, *Plectonema boryanum* UTEX 485, has been used to recover Au NPs from Au (III)-chloride. In this process, several intermediary products such as Au (I) sulfide were generated. Such intermediary compounds were treated were required to be treated with another sulfate-reducing bacterium to recover Au NPs (Mohanpuria et al., 2008).

## 4 Synthesis and Applications of Nanoparticles Synthesized by Microorganisms

Biosynthesized NPs have been used in a variety of applications and much attention has given to NPs derived from precious metals. In this section, microbial synthesis methods and applications of Ag, Au, Pt, and Pd NPs are discussed.

### 4.1 Silver (Ag) Nanoparticles

Metallic Ag has been used in medicine, food, agriculture, textiles, plastics, cosmetics, catalysts, and in the production of coins (currency). Despite the view that the soluble forms of Ag can cause potential harm to the humans, Ag NPs are widely used in various industries. Some researchers have claimed it is relatively nontoxic and noncarcinogenic.

The mechanisms of Ag NP activity is yet to be explored and some researchers attribute it with the same the mechanisms as  $\text{Ag}^+$  but this may not be true. Ag NPs can penetrate the bacterial cell via cell wall while at the same time the mechanisms existing in terms of protecting the cell wall are also affected. Moreover, plasma membrane permeability and physiological processes are also ceased, affecting the normal functioning of the cells. Interactions can take place with the S-containing proteins of the cell wall causing irreversible damages to the cell wall (Li et al., 2008). These cidal effects are dependent upon the size, shape, and surface charge of the NPs.

In medicine, Ag NPs have been widely been used in implant surgeries and applied in wound dressings. Studies have proven the ability of aiding bone and skin tissue regeneration using Ag NP-containing nanofibers. Furthermore, medical appliances such as catheters and heart and bone implants are permeated

with Ag NPs to prevent the pathogenic bacterial growth on the surfaces. Additionally, Ag and Au are using in various biosensing and bioimaging applications. They are used in various cancer related protein detecting systems. In bioimaging, Ag NPs are widely used to monitor dynamic events over long periods. Due to good antiseptic properties, Ag NPs are contained in cosmetics and skin therapeutics and related drugs to treat acne. NP-coated papers in the food industry may play a critical role in the future. Ag NPs have even been incorporated into paints to prevent antimicrobial growth occurring on walls.

Various microorganisms have been used for controlling human pathogenic microorganisms that cause infections by food poisoning, wound infections, and rejection of organ transplants. *Staphylococcus aureus* is one such major disrupting microorganisms that affect wounds. Cotton fabrics that used to strap wounds have been treated with Ag NPs produced by *Fusarium oxysporum* (Duran et al., 2016). *Bacillus pumilus*, *B. persicus*, and *B. licheniformis* have also been used to synthesize Ag NPs and have shown better in vitro antimicrobial properties against important human pathogen antiviral activities in plants affected by Bean yellow mosaic virus (Anasane et al., 2016). Furthermore, the effect against both *S. aureus* and *E. coli* were tested by El-Rafie et al. (2010) and proved to be effective in suppressing their growth. Extracellular biosynthesis of Ag NPs by *P. columellifera* subsp. *pallida* and its antifungal activity against certain human pathogenic fungi, including *Malassezia furfur*, *Trichophyton rubrum*, *Candida albicans*, and *C. tropicalis*, were reported by Essam et al. (2015). *Streptomyces hygroscopicus*-produced Ag NPs have tested against *B. subtilis*, *Enterococcus faecalis*, *Escherichia coli*, and *Salmonella typhimurium* (Sadhasivam et al., 2012). *A. niger*-mediated Ag NPs have shown to be effective in terms of wound healing activity (Sundaramoorthi et al., 2009). *A. niger* L3 (NEA) and *Trichoderma longibrachiatum* L2 (TEA) mediated synthesized Ag NPs have shown better anticoagulant and thrombolytic activities in human blood (Elegbede et al., 2018). *Alternaria alternata*-synthesized Ag NPs have shown to be effective against *Phoma spp.* that reduce the quality of fibers (cotton), *Fusarium semitectum* that cause fusarium toxin production in grains, *Trichoderma spp.* (Gajbhiye et al., 2009). Ag NPs produced by *Amylomyces rouxii* have also proved effective against *C. albicans*, a human gut-inhabiting yeast species which can act as an opportunistic pathogen and *F. oxysporum* that produces mycotoxins in grains while being pathogenic to plants (Musarrat et al., 2010). Ag NPs produced by *A. ochraceus* were effective in controlling phage viruses such as the M13 phage virus (Vijayakumar and Prasad, 2009). *Phenerochaete chrysosporium* (MTCC-787), a crust fungi-mediated synthesis of Ag NPs, was reported by Saravanan et al. (2018a, b) and the resulted Ag NPs were further tested against human pathogenic bacteria *P. aeruginosa*, *K. pneumoniae*, *S. aureus*, and *S. epidermidis*. They further demonstrated the nontoxic nature of the same species at 12.5 µg/mL towards fibroblast cells.

In another study, extracellular synthesis of Ag NPs from *B. brevis* (NCIM 2533) was achieved and demonstrated the in vitro antibacterial efficacy against



*S. typhi* and *S. aureus* (Saravanan et al., 2018a, b). Ag NPs produced by *Lactobacillus fermentum* have also found to be effective in disrupting Bacteriophage UZ1 (De Gusseme et al., 2010). Antimicrobial activity of Ag NPs synthesized by *Pleurotus sajor-caju* were tested against *S. aureus* and *K. pneumonia* (Vigneshwaran et al., 2007). Ag NPs produced by *Pestalotia* spp. have been tested against *S. aureus* and *S. typhi* (Raheman et al., 2011). In addition to the pathogenic suppression, certain pesticidal activities were also shown by such nanoparticles. For instance mosquito larvicidal activity was shown in larvae of *Culex quinquefasciatus* and *Aedes aegypti* with *B. megaterium*-synthesized Ag NPs (Banu and Balasubramanian, 2015). The endophytic fungi strain *Phomopsis liquidambaris* strain SA1 has been experimented to synthesize Ag NPs and proved to be effective against *A. aegypti* and *C. quinquefasciatus* in a dose-dependent manner (Seetharaman et al., 2018). Ag NPs synthesized by *P. mandelii* have also shown cidal activity against larvae of *Anopheles subpicatus* and *C. tritaeniorhynchus* (Mageswari et al. 2015). Furthermore Ag NPs synthesized by *B. amyloliquefaciens* and *B. subtilis* have also been shown as effective in suppressing the growth of mosquito colonies of *C. pipiens pallens* (Fouad et al. 2016). Ag NPs can affect the with larval cell membranes, by changing the cell membrane permeability and then the molting process, while damaging the cellular DNA and S-containing proteins.

## 4.2 Gold (Au) Nanoparticles

Au NPs are also considered as potential candidates in various biomedical applications including cancer therapy. *Streptomyces clavuligerus*-mediated Au NPs were synthesized and showed to be nontoxic, biocompatible, and of an antiproliferative nature that induced apoptosis (Kumar et al., 2015). Lengke et al. (2006a) revealed that *P. boryanum*, which is a filamentous cyanobacteria, can induce biogenesis of Au NPs less than 25 nm from  $\text{Au}(\text{S}_2\text{O}_3)_2^{2-}$ . Furthermore, Lengke et al. (2006b) demonstrated Au(I) sulfide precipitation on the cell wall of the same cyanobacterium species and then forming much smaller nanoparticles than observed in the previous case. Au NPs were synthesized by Ahiwale et al. (2017) using a bacteriophage and 0.2 mM concentration of synthesized Au NPs inhibited 80% of biofilm formation by *P. aeruginosa*, a human pathogen. Smaller-sized Au NPs were synthesized by *B. subtilis* isolated from Au mines in India and they were effective in catalyzing the degradation of methylene blue (Srinath et al., 2018). Biosynthesis of Au NPs using *P. denitrificans* exudates was demonstrated using 100 ppm aurochlorate (aq) (Mewada et al., 2017). Au NPs were synthesized from  $\text{HAuCl}_4$  using *Streptomyces* sp. strain NH21 isolated from acidic forest soil. Furthermore, in vitro antibacterial activity and minimal inhibitory concentration of synthesized Au NPs were determined against *B. subtilis* ATTC 6633, *S. aureus* ATTC 6338, *K. pneumoniae* ATTC 700603, *P. aeruginosa* ATTC 10145, *E. coli* ATTC 8739, *Proteus mirabilis*, and *Salmonella infantis* (Składanowski et al., 2017).



Bing et al. (2018) synthesized Au NPs using a hydrogen-producing hyperthermophilic bacterial strain *Caldicellulosiruptor changbaiensis*. The smallest Au NPs exhibited the highest peroxidase activity over a broad range of pH and the activity was different to the chemically-synthesized ones. Furthermore, they showed excellent antibacterial capability against various Gram-positive and Gram-negative bacteria and dispersing bacterial biofilms under both in vitro and in vivo conditions. Synthesis of Au NPs using *Salmonella enterica* subsp. *Enterica* serovar Typhi isolated from blood and stool samples of infected patients was reported by Mortazavi et al. (2017). Endosymbiont bacterium, *Aneurinibacillus migulanus*-mediated synthesis of Au NPs was reported by Syed et al. (2017), while proving their ability to suppress certain human pathogens. Biogenic synthesis of Au NPs by *Halomonas salina*, a halophilic proteobacterium, was reported by Shah et al. (2017). Another study demonstrated the formation of Au NPs using 29 thermophilic filamentous fungi by reducing Au (III) to Au (0) (Molnár et al., 2018). In another study, cell-free extracts of *Aspergillus* sp. WL-Au were employed to synthesize Au NPs and proved their catalytic reduction of 4-nitrophenol and this capacity was much higher than other biological and conventional chemical means (Shen et al., 2017). Similarly extracellular biosynthesis of smaller Au NPs was performed by Roy et al. (2016) and showed no significant cytotoxicity in A549 cells compared to chloroaurate. *Klebsormidium flaccidum*, a filamentous charophyte green algae-mediated Au NPs were produced by Sicard et al. (2010) and tested to be used as photosynthesis-based environmental biosensor. Au NPs were produced using *Thermomonospora curvata*, *T. fusca*, and *T. chromogena* by Torres-Chavolla et al. (2010) and tested as enhanced biosensors. Au NPs produced by *E. coli* were tested for the study of direct electrochemistry of hemoglobin (Du et al., 2007). Relatively higher-sized Au NPs were obtained from the reaction of Au salt with cell free aqueous extract of cyanobacterium *Leptolyngbya* JSC-1 as a medium of reducing and stabilizing agents to produce Au NPs which was antibacterial against *E. coli* and *S. aureus* due to membrane damage and cell disruption, due to prompting the production of reactive oxygen species (ROS) (Zada et al., 2018).

### 4.3 Palladium (Pd) Nanoparticles

Applications of Pd NPs mainly exist in relation to environmental remediation activities such as dehalogenation. The catalytic ability of Pd NPs to trigger the chemical reactions is used in this process. Pd NPs are widely used to dehalogenate persistent, bioaccumulative, and toxic (PBT) pollutants which are not naturally degraded, including certain pesticides (such as DDT) and PCBs. *S. oneidensis* is one of the bacterial species that has been used to synthesize Pd NPs which have been employed in dehalogenation of various chemicals such as chlorophenol, PCBs, lindane, trichloroethylene, and diatrizoate (De Windt et al., 2006; Mertens et al., 2007; Hennebel et al., 2009a, b, 2010;

De Gusseme et al., 2011). Furthermore, *Desulfovibrio* species such as *D. vulgaris* and *D. desulfuricans* have been used to experiment CP, PCB and penta-CP dehalogenation (Baxter-Plant et al., 2003, 2004; Harrad et al., 2007; Redwood et al., 2008; Deplanche et al., 2009). Pd NPs produced by the bacterium *P. putida* have been successfully used to remove certain pesticide pollutants (Forrez et al., 2011). Moreover, *Desulfovibrio*-produced Pd NPs have been shown to be effective in reducing Cr at higher oxidation state to lower states of III (Mabbett and Macaskie, 2002; Humphries et al., 2006; Mabbett et al., 2006). Moreover *Desulfovibrio*-derived Pd NPs have been employed in hydrogenation of various chemicals, reduction, and selective dehalogenation of certain solvents (Creamer et al., 2007; Creamer et al., 2008; Bennett et al., 2010). In addition, microbial-synthesized Pd NPs have been widely experimented with in fuel cell electrodes (*Saccharomyces oneidensis*, *D. desulfuricans*, *E. coli*, *Cupriavidus metallidurans*) (Orozco et al., 2010; Yong et al., 2010; Ogi et al., 2011) and biohydrogen (*E. coli*) (Macaskie et al., 2005). Martins et al. (2017) reported on *D. vulgaris*-mediated biosynthesis of Pd and Pt nanoparticles and their potential application in catalyzing the removal of certain pharmaceutical products such as antibiotics and endocrine disrupting compounds from effluents.

#### 4.4 Platinum (Pt) Nanoparticles

Pt nanoparticles are well known for their capabilities in terms of catalyzing chemical reactions, biosensing applications such as detection of cancerous cells. Compared to other precious metals such as Au, Ag, and Pd NPs, there exist a limited number of studies pertaining to Pt NPs synthesized by microbes and their potential applications. Applications of Pt NPs in medicine were comprehensively described by Pedone et al. (2017). They discuss its catalytic activity, ability to reduce the intracellular reactive oxygen species through enzymatic activity, antiinflammatory ability, influence of certain physicochemical parameters, and surface functionalization that change cytotoxicity. Filamentous cyanobacteria have also employed in biosynthesis mechanisms, for instance *P. boryanum* UTEX 485 has been used to produce Pt NPs in a range of sizes (Lengke et al. 2006c). Pt NPs synthesized by *E. coli* have been tested for biosorption and biorecovery applications (Won et al., 2010). Pt NPs produced with *S. cerevisiae* have been experimented with in biorecovery applications and in fuel cell electrodes (Dimitriadis et al., 2007). Similarly, Attard et al. (2012) also synthesized Pt NPs using *E. coli* (MC4100). Much smaller Pt NPs were produced using the fungus *Neurospora crassa* (Castro-Longoria et al. 2012). Bennett et al. (2012) also demonstrated the catalysis ability of *E. coli*-assisted biosynthesized Pt as an analog to a Pt/graphite catalyst used in hydrogenation of 1,4-butyne diol. Similarly, Pt NPs were produced using *F. oxysporum* by both intracellular and extracellular means (Riddin et al. 2006).

## 4.5 Bimetallic Precious Nanoparticles

Bimetallic precious nanoparticles are also gaining greater attention due to their unique properties especially in terms of catalyzing certain reactions. Bimetallic NPs are composed of two metal components and various combinations of precious bimetal nanoparticles produced with the involvement of microorganisms. Bimetallic/core-shell NPs are more economic than other NPs due to their durability, activity, and wider array of applications. They possess unique structural features, can be simply produced and easily controlled, and exert activity in a range of chemical conditions. Due to these features they can be widely used in medical diagnostic applications (Khatami et al., 2018). Pd, Pt, and Pd-Pt nanoparticles have been synthesized using *S. oneidensis* MR-1 and all NPs showed higher efficiency in reducing 4-nitrophenol by NaBH<sub>4</sub> (Tuo et al., 2017). Bimetallic Pd-Pt catalysts have been experimented with in various reactions, including the oxidation of methanol, preferential oxidation reactions, the reduction of oxygen reactions, dehalogenation mediated by photocatalysis, and hydrogen storage (Tuo et al., 2017). Au-Ag NPs synthesized by *F. oxysporum* and *F. semitectum* have been identified as alloys and are still under investigation (Senapati et al., 2005; Sawle et al., 2008). Au-Pd NPs have also been synthesized with the involvement of *E.coli* (Deplanche et al., 2012).

## 5 Recovery of Precious Metal From E-waste as a Branch of Municipal Solid Waste Management

It is important to link the E-waste recovery process with an integrated waste management process at an urban, regional, or national scale in order to understand the influence of each technology in a broader scale. Lifecycle analysis (LCA) is the tool that is used in this context to assess the impact of each technology and arrive at the optimum pathway to process waste on a larger scale. Hence, it is important to understand the solid waste management process at an urban, regional, or national scale in order to understand the feasibility of implementing biological methods to recover precious metals from E-waste. Towards this objective, this section provides a concise overview about the waste management strategies used at the urban scale (focusing more on municipal solid waste management [MSW]) and the importance of E-waste recovery using biological methods from the LCA perspective.

Policy-makers try use the concept of reduce, reuse, and recover in order to manage waste sustainably. The classic approach towards waste management is direct handling of the solid waste using a single process such as landfill or direct incineration. The composition of the waste and possibility to recover either valuable materials or energy from solid waste is not considered in such instances, which leads to a strong environmental impact. However, the classical approach towards MSW is changing fast. As a result, a major change is taking

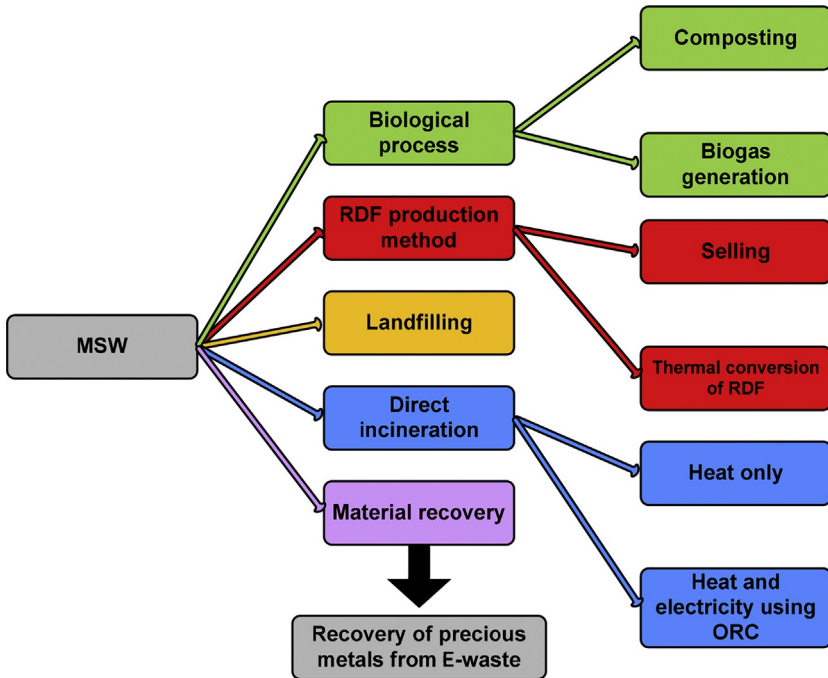


FIG. 6.1 Multiple pathways for processing different components of municipal solid waste.

place in solid waste processing by replacing the direct single-step waste management strategy with integrated municipal solid waste management systems (Perera et al., 2011, 2013). Such integrated solutions consist of multiple technologies that handle the different parts of the waste. As seen in Fig. 6.1, five different colors represent the five different main pathways for different components of the solid waste to be processed in an integrated waste management system. There are more than one way to carry out each pathway. For example biological processing can be achieved resulting in either biogas or compost. Furthermore, there are number of different ways to perform biogas generation. Precious material recovery from E-waste belongs to the material recovery branch.

Optimization and lifecycle assessment of the superstructure of the integrated waste management plays a vital role in deriving optimum pathways to process municipal solid waste management. The interrelationship among different waste processing methods, lifecycle cost, lifecycle environmental impact, health impact, and social acceptance are considered the key performance indicators. A number of recent studies have focused on different biorecovery methods to assist E-waste recovery. However, most of these studies limit their scope to the assessment of the process efficiency in recovering precious metals. A detailed assessment on the lifecycle cost, reduction of the environmental

impact, improvement in health conditions, etc. have not been addressed in these studies. It hinders the incorporation of such methods into the superstructure of the municipal solid waste management. Therefore, this study highlights the importance of conducting detail lifecycle assessment on the biorecovery methods to support integration into the super structure of the municipal solid waste management system in the future.

## 6 Concluding Remarks and Future Implications

The synthesis of NPs using microbes for application in a variety of fields has been gaining greater attention for nearly two decades and in future this technology will be in high demand. The economic feasibility over conventional chemical means such as low-cost nature performance under standard environments (temperatures and pressures) have favored the technology's adoption. Furthermore the technology can be scaled up. The natural capability of certain microbes in facilitating redox chemistries is the base of this technology.

WEEE will gain a higher demand in the future due to its potential as a good source or an artificial ore for the synthesis of precious NPs. However, strategies should be explored to prevent interrupting subreactions due to the presence of other metals and to enhance the purity of synthesized nanoparticles without other contaminants such as Hg and Pb, which are constituents of WEEE. However, the current research on microbe-mediated synthesis of nanoparticles using WEEE is limited, therefore more studies should be conducted to explore the potential of using WEEE as a source of precious metals. Irrespective of the mean of synthesis in general, NPs possess various properties due to a variety of capping chemicals. These are unique to various organisms and depending on the capping agents, the properties can also be changed and have a much better performance relative to chemically-synthesized nanoparticles. However, there are challenges associated with this method such as contamination with the microbe-mediated chemicals or cells. There is also a relatively higher time associated with the process of synthesis when compared to chemical and physical methods. At the same time, the size of the yielding NPd and their monodispersity and durability are of major concern. Therefore, we need to find better strategies to overcome the highly time-consuming nature of the process, achieving monodispersity, long-term stability, and controlling the size of the finished product. Furthermore, more efforts should be made to discover the mechanisms related to extracellular synthesis of NPs due to incurring additional efforts to recover nanoparticles from the interior of the cells. A greater need also exists to understand the exact mechanisms of NP-mediated reactions within biological systems under different concentrations and toxic thresholds. Furthermore, in the future, high-scale production may easily be achieved through genetic engineering approaches and the genomes of potential microbes may be manipulated to enhance the metal ion conversion capacity into nanoparticles.

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