1. Project title: Recycling of waste electronics using environmentally sustainable processes

2. Supervisors: Prof. Jason Love (Chemistry), Dr Carole Morrison (Chemistry), Dr Bryne Ngwenya (Geosciences)

3. CASE partnership: n/a

4. Primary supervisor contact email: jason.love@ed.ac.uk

5. Project background: Every year 50 million metric tonnes of electronic waste (e-waste) are generated worldwide, a figure that is rising due to constant updating of consumer electronics. Best estimates show that only 30% of e-waste is recycled, yet the metal content of printed circuit boards (PCBs) can be as high as 40%, with many metals, such as Cu, Au, Ag and Pt present in quantities greatly exceeding that of their primary ores.[1] The average smart phone also contains eight rare earth elements, of which less than 1% are currently recycled. Moreover, toxic heavy metals (e.g. Pb, Cd, Sn and As) present in e-waste can leach into soil and groundwater from landfill sites. Compared with conventional mining practice, urban mining therefore offers huge potential to reduce environmental impact, lower energy costs, conserve natural resources, and provide resource security, especially in the context of lack of primary mining deposits in the UK and EU. In light of this, we have recently developed new chemistry that allows the selectively recovery gold from the mixture of metals commonly phone in a mobile phone.[2] We now wish to utilise these results to develop a new process for e-waste recycling that ensures best environmental and societal practice and could be used simply by operators in developing nations (Figure 1). For this, we will develop strategies that combine the bioleaching of e-waste with solvent extraction techniques.

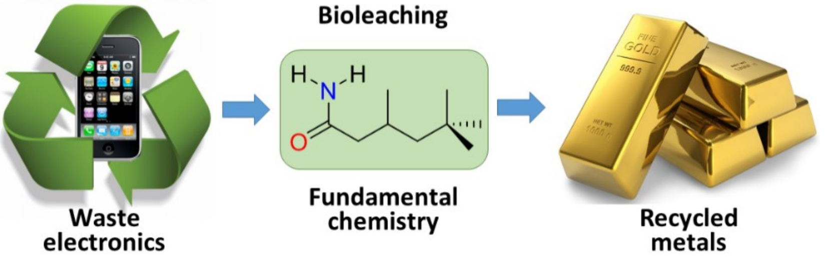


Figure 1. Schematic showing how bioleaching combined with solvent extraction can be exploited to recover metals from e-waste.

6. Key research questions:

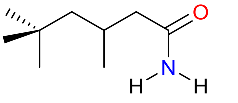
- Can bioleaching methods be used on electronic waste to provide a selective metal feed stream suitable for separations chemistry?
- Is it possible to design reagents that can selectively extract metals found in e-waste feed streams?
- Can the modes of actions of these processes be understood such that further improvements can be made in the generic metal recovery field?
- Will these advances decrease the environmental impact of e-waste and move towards a more circular economy?

7. Methodology: This project will comprise research from both Schools of Chemistry and Geosciences in order to make a general impact in the e-waste recycling field. The two aspects of research are intrinsically linked as the reagents used in the separation process will depend upon the nature of the feed provided by bioleaching.

Bioleaching: Conventional methods of metal beneficiation through comminution, grinding, separation (magnetic or floatation) and acid-leaching demands major energy and reagent costs to produce metal concentrates, and leave a large environmental footprint from CO_2 emissions and soil and groundwater contamination. It is therefore desirable to develop sustainable beneficiation techniques with lower energy costs and improved environmental legacies is essential. Bioleaching uses microorganisms to facilitate leaching of minerals,[3] and offers significant economic benefits over traditional metallurgy, including exploitation of small deposits in remote locations due to reduced infrastructure costs, and low energy input through operation at ambient pressure and temperature.

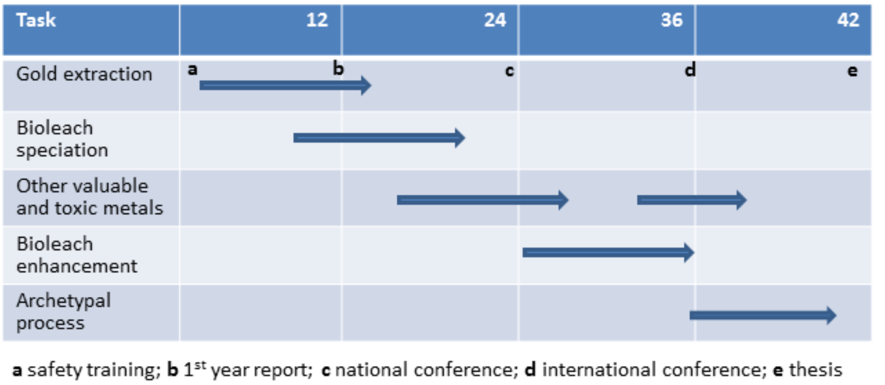
Although bioleaching is used commercially to process copper, zinc, nickel and cobalt ores, there is no commercial use of bio-leaching of e-waste streams despite excellent potential for preferential leaching of metals such as gold which aids in downstream separation.[4] Current applications of bioleaching are dominated by sulfidic ores and mostly exploit chemilithotrophic iron or sulfide oxidisers to generate oxidise sulfuric acid. In this project, we will exploit such bacteria by feeding them small amounts of pyrite (FeS_2) mixed with e-waste to generate the H_2SO_4 necessary to dissolve the desired metals. We will also evaluate the use of cyanobacteria to focus particularly on the leaching of gold from e-waste as gold cyanoaurate $Au(CN)_2^-$ as an alternative to traditional cyanide leaching. The resulting leachates will act as feedstock to the solvent separation process as described below. Additional characterisation studies will involve X-ray absorption spectroscopy to determine the speciation of different metals in solution.

Solvent extraction: The use of a suitable extracting reagent in a solvent extraction process can dramatically improve the efficiency of the process, facilitating the recycling of reagents, offering an enhanced materials balance, and lessening waste deposition.[5] In the first instance, we will study the extraction of singular metals, e.g. gold, from bioleached e-waste streams in order to determine effective phase transfer and selectivity. We will use spectroscopic (e.g. NMR spectroscopy, ESI-MS) and analytical (e.g. ICP-OES) approaches to determine the formulation of the species extracted, and use this information in computational work to model the extraction process and inform future experimental design. Two synergistic strands will be taken to modelling the solvent extraction process comprising classical molecular dynamics and more in-depth ab initio studies to identify, and quantify, the key ligand/target interactions that drive the extraction process and that could be refined to offer routes towards selective metal recovery from e-waste.



1° amide for Au recovery

Our initial focus will be to understand our new reagent used in gold recovery (inset),[2] in particular why it is so effective compared to the state-of-the-art and similar analogues. For this, we will make use of experimental work and collaborations in spectroscopic techniques such as EXAFS, Total Scattering techniques, and Mossbauer spectroscopy to understand speciation and structure. We will subsequently look at the recovery of other valuable metals such as Ag, Pt, and Rh, followed by potentially toxic metals such as Pb and As to develop a process that minimizes metal release into the environment. The investigations, coupled with those described above for bioleaching, will lead to new publications, further grant applications and the potential for patent protection.



a safety training; **b** 1st year report; **c** national conference; **d** international conference; **e** thesis

Figure 2. Project timeline including experimental, analytical, and computational work in each task

8. Training: A comprehensive training programme will be provided comprising both specialist scientific training and generic transferable and professional skills. Project-specific training in spectroscopic analysis, data collection and manipulation, analytical methods, geomicrobiology, safe working in a chemical environment, and computational modelling and analysis will be provided.

9. Requirements: The student will require a strong background in chemistry, either through a good Chemistry degree (2.1 or 1st class) or related fields. Because of the multidisciplinary nature of this research, experience in metal coordination chemistry would be advantageous, plus some background in geochemistry and biochemistry.

10. Further reading or any references referred to in the proposal:

[1] Hagelüken, C. & Corti, C. W. "Recycling of gold from electronics: cost-effective use through design for recycling," *Gold Bulletin* **2010**, *43*, 209; [2] E. D. Doidge *et al.*, "A simple primary amide for the selective recovery of gold from secondary resources," *Angew. Chem. Int. Ed.*, **2016**, *55*, 12436; [3] C. L. Brierley, J. A. Brierley, *Appl. Microbiol. Biotechnol.*, "Progress in bioleaching: part B: applications of microbial processes by the minerals industries," 2013, **97**, 7543; [4] Electronic Waste- recycling techniques, Eds H. M. Veit, A. M. Bernardes, Springer

International Publishing, Switzerland, 2015; [5] A. M. Wilson *et al*., "Solvent extraction: the coordination chemistry behind extractive metallurgy," *Chem. Soc. Rev.*, **2014**, *43*, 123

11. The application procedure is outlined at: http://e3dtp.geos.ed.ac.uk/apply.html

The School of Chemistry holds a Silver Athena SWAN award in recognition of our commitment to advance gender equality in higher education. The University is a member of the Race Equality Charter and is a Stonewall Scotland Diversity Champion, actively promoting LGBT equality. The University has a range of initiatives to support a family friendly working environment. See the University Initiatives website for further information https://www.ed.ac.uk/equality.