Bioleaching for resource recovery from low-grade wastes like fly and bottom ashes from municipal incinerators: A SWOT analysis

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Highlights

- Circular economy depends on resource recovery from wastes
- Strengths, Weaknesses, Opportunities, and Threats (SWOT) identified for bioleaching
- Bioleaching can be a sustainable technique for metal recovery from low-grade wastes
- Resource recovery demands integrated policy and regulatory framework

Abstract

Bioleaching (or microbial leaching) is a biohydrometallurgical technology that can be applied for metal recovery from anthropogenic waste streams. In particular, fly ashes and bottom ashes of municipal solid waste incineration (MSWI) can be used as a target material for biomining. Globally, approximately 46 million tonnes of MSWI ashes are produced annually. Currently landfilled or used as aggregate, these contain large amounts of marketable metals, equivalent to low-grade ores. There is opportunity to recover critical materials as the circular economy demands, using mesophile, moderately thermophile, and extremophile microorganisms for bioleaching. A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis was developed to assess the potential of this biotechnology to recover critical metals

from MSWI wastes. Bioleaching has potential as a sustainable technology for resource recovery and enhanced waste management. However, stakeholders can only reap the full benefits of bioleaching by addressing both the technical engineering challenges and regulatory requirements needed to realise and integrated approach to resource use.

Keywords: Circular economy; critical raw materials; biotechnology; municipal solid waste incineration – MSWI; waste management

1. Introduction

Our current patterns of consumption are leading to the exhaustion of planetary resources, while simultaneously generating pollution and threatening our survival as a species. There is an urgent need for a change in paradigm in waste management to efficiently recover resources (energy, metals, nutrients) from waste streams, making industrial and urban processes more efficient. According to the recent UN Global Resources Outlook, extractive industries are responsible for half of the global carbon emissions (Oberle et al., 2019). Resource extraction and processing caused 90% of biodiversity loss and water stress, which puts a more dangerous level of pressure on climate and natural life support systems than previously thought. Resources are being extracted three times faster than in 1970, even though the population has only doubled in that time, according to the same report. The United Nations Sustainable Development Goals (SDG) set a target to achieve sustainable management and efficient use of natural resources by 2030, by decoupling economic growth from resource use and environmental degradation. This is to achieved by improved resource efficiency, decreased reliance on raw materials, and increased recycling to reduce environmental pressure and impact. “Circular economy” and “zero waste” are buzzwords today, but both goals still look unattainable (Velenturf et al., 2019).

Metals are valuable raw materials for the global economy, and key components of various products such as low-carbon energy technologies, electric vehicles, and electronic and biomedical devices. Large quantities of critical and scarce metals, such as platinum group metals (PGM), rare earth elements (REE), cobalt, vanadium, selenium, and tellurium are required for storage and production of renewable energies, catalytic processes, digital communication, and green technologies (Hofmann et al., 2018; Işıldar et al., 2019). Raw materials and metals are considered critical when they have high economic importance combined with an elevated risk of supply, mainly resulting from high production in countries with poor governance (geopolitical instability), limited material replaceability, and low end-of-life recycling rates (EC, 2017).

Municipal solid waste incineration (MSWI) has been globally adopted for the management of vast amounts of waste (a global average of 130 tonnes per year) (Joseph et al., 2018), as it allows energy recovery and reduction in the volume of waste sent to landfill. However, the incineration of municipal solid waste destroys technical value given that once the energy value of waste has been recovered by burning, it is no longer available to the circular economy (Purnell, 2019). Coarse metals (>2mm) remaining in fly ashes and bottom ashes are typically recovered, and the residual fraction is recycled as construction material. However, low but significant quantities of high-tech, high-value metals remain in the residual material. Estimated annual flows of these high-value metals are in the order of tens of kg and a total content comparable to low-grade active mines (Funari et al., 2015). The potential for urban mining and recovery of secondary resources from MSWI residues is, therefore, promising as a way of closing the loop within a circular economy (Simon and Holm, 2018).

Given the low metal concentrations, economic feasibility is dependent on using low cost, sustainable technologies, such as bioleaching. Bioleaching is commercially used for the recovery of metals from low and waste grade ores, in particular for copper (Gomes et al., 2018).

These ores would typically be uneconomic to process using conventional comminution-concentration-flotation routes. Bioleaching uses microorganisms isolated from natural settings (e.g. extreme environments, acid mine drainage) to generate mineral or organic acid (as metabolites) and improve metal solubility by enzymatic reactions. Bioleaching can be performed by direct contact (primary bioleaching) and by indirect leaching (or secondary bioleaching). The latter only uses the acid produced by bacteria to recover metals without a direct inoculation. This approach may be best suited in some circumstances, e.g. for alkaline wastes where the conditions are not favourable for the survival of the typically acidophilic bacteria However, both approaches are acknowledged to lessen environmental and economic drawbacks during treatment of anthropogenic waste, compared to using mineral acids (Funari et al., 2017).

This paper aims to assess opportunities and limitations associated with bioleaching of low-grade wastes for metal recovery, in the context of the circular economy. It is beyond the scope of this study to provide a comprehensive review of the latest developments of bioleaching. In recent years, there has been an increasing amount of literature on bioleaching, with several extensive reviews covering the topic (Auerbach et al., 2019; Pollmann et al., 2018; Sethurajan et al., 2018; Srichandan et al., 2019). Our objectives are to focus on practical aspects and limitations that remain obstacles for the full implementation of bioleaching as a crucial tool for the circular economy.

2. Bioleaching as an alternative for resource recovery from MSWI waste

Current alternatives used at industrial scale for resource recovery from MSWI fly ashes are based on acid leaching (e.g. FLUWA process), and washing processes for salt recovery (e.g. HALOSEP®) (Quina et al., 2018). At lab scale, hydrometallurgical processes for copper and zinc recovery (Tang et al., 2018), electrodialytic processes (Kirkelund et al., 2015), and treatment processes combining leaching, selective extraction and adsorption (Tang et al., 2019) have shown promising results, but are still at low technology readiness levels (TRL).

A recent review of the different removal techniques for metals from fly ash compared bioleaching, carrier in pulp method, chemical extraction with different acids, alkaline leachates and chelating agents, chloride evaporation process, electrodialytic and thermal treatments (Meer and Nazir, 2018). The authors concluded that the selection of the best process depends on the type of fly ash and target metal(s), but also of factors like cost, time and energy (Meer and Nazir, 2018).

Bioleaching of bottom ash (BA) and fly ash (FA) with a mixed culture isolated from a natural system showed good yields of metal extraction, with more than 90% Zn, Cu, and 10% Pb removed from FA; while 100% Cu, 80% Zn and 20% Pb were removed from BA samples (Funari et al., 2019). Bioleaching of bottom ashes with pure cultures *Acidithiobacillus ferrooxidans* or *Leptospirillum ferrooxidans,* or a mixture of *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans* in batch tests showed that Al, Cr, Cu, Ni, Mn and the rare earth elements Ce, La, and Er were significantly more extracted with iron-oxidizing bacteria compared to abiotic controls (Auerbach et al., 2019). The results are encouraging for industrial application to recover concentrated metals like Al and Cu, simultaneously reducing the cost of landfilling the remaining residues. Continuous heap bioleaching at lab scale showed leaching yields for zinc and copper between 18–53% and 6–44% (Mäkinen et al., 2019), but also highlighted the need for further optimisation, in particular regarding acid addition and aeration.

Bioleaching using alkaline autochthonous extremophiles isolated from a fly ash landfill site showed that *Alkalibacterium sp.* TRTYP6 could recover 52% of Cu (Ramanathan and Ting, 2016). The use of fungi for fly ash bioleaching showed that fungal morphology of *Aspergillus* *niger* was significantly affected during one-step and two-step bioleaching, with precipitation of calcium oxalate hydrate crystals at the surface of hyphae (Xu et al., 2014).

Several factors can influence bioleaching efficacy, such as pH, temperature, pulp density, redox potential, microorganisms or communities involved, particle size, oxygen and iron concentrations, and wastes mineralogy (Sethurajan et al., 2018). Also, metal bioleaching is influenced by biomass concentration, metal tolerance of microorganisms, type and amount of metabolic products released into the medium, contact time, and pretreatment (e.g. heating) and has to be assessed case by case (Pollmann et al., 2018). Nevertheless, bioleaching can be a flexible and environmentally friendly alternative for conventional processes, as it allows the recovery of valuable resources, but can also reduce the toxicity of the waste for further reuse in other applications (e.g. aggregate materials) (Auerbach et al., 2019).

3. SWOT analysis

Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is a framework technique used in business to facilitate the development of a sustainable market niche by uncovering new outlooks and identifying problems that would hinder progress (Miller, 2007). Table 1 summarises a SWOT analysis for the use of bioleaching for metal recovery from MSWI fly ashes and bottom ashes.

Table 1. Strengths, Weaknesses, Opportunity and Threats (SWOT) analysis for bioleaching for resource recovery from MSWI residues.

Strengths	**Weaknesses**
- Lower environmental footprint (avoids strong mineral acids used in hydrometallurgy methods, lower energy consumption) - Not labour intensive - Different microorganisms (fungi, isolate/mixed acidophilic/alkaline bacteria) can be used for bioleaching - Bioleaching can be achieved in one-step, two-step and spent medium-step - Minimal investment and low operating costs compared with hydrometallurgy methods - Can be performed *in situ* - Technology readiness level 9 for primary ores - Can be used to reduce contamination of wastes/biostabilization	- Depends on quantities/concentrations of metals in wastes - Presents slow dissolution kinetics and low metal leaching yield - Heap bioleaching can be space demanding - Adaptation of microorganisms to waste materials is critical - Alkaline wastes are not favourable to the growth of acidophile bacteria - More data on alkaline bioleaching are needed - Not fully reproducible, as it depends on the feedstock material - Inhibitory layers hinder cell-mineral interaction (passivation effects) - Lack of research dedicated to process development and reactor design - No pilot-scale applications for anthropogenic streams such as FA and BA from MSWI
Opportunities	**Threats**
- Recovery of metals from low-grade ores and wastes can be a potential offset for remediation and operation costs in both operating and legacy sites - Development and use of bioelectrochemical systems for energy production and metal recovery - Minimise the environmental impacts of raw materials extraction - Fine-tuned bioleaching to enhance selectivity to targeted metals - Accelerate carbonation and carbon sequestration using microorganisms	- Hight volatility of markets and metal prices - Low cost of waste disposal in landfill - Low mineral extraction costs ("mineralogical barrier") - No alternatives for the downstream processing of excessive biomass produced - Lack of satisfactory coverage for substrate materials and inocula - Lack of work practices may lead to poor reproducibility - Higher bioavailability of potentially toxic metals

3.1 Strengths

Bioleaching is a technology considered environmentally friendly, for being less aggressive (lower use of concentrated acids/bases) and energy-intensive than traditional hydrometallurgy methods. It can be performed *in situ*, as heap bioleaching, with minimal investment, and low operating costs. The process is not labour-intensive since only a few process parameters need essential monitoring and control. Unskilled operators can perform the key maintenance operations with minimal risks (e.g., no use of strong acids like hydrofluoric acid), including the manipulation of bacterial matter. MSWI bioleaching bacteria show low biological hazard and risk of contamination, with no identified risks to humans, especially those cultures isolated from natural systems of well-known characteristics. Moreover, bioleaching combines traditional hydrometallurgical methods effortlessly and in a cost-effective manner, because it does not require highly sophisticated monitoring and control instruments, the implementation of which can be expensive. Pure bacterial cultures, mixed (acidophilic or alkaline) bacteria, archaea, fungi, algae and plants metabolites can be used for bioleaching of different metal-bearing wastes. The bioleaching process can be achieved by one-step, two-step and spent medium-step, both in batch or continuous modes and showed promising results on the extraction of several metals (Ni, Co, Mo, V, Fe, Zn, Cu, Cr, Cd, W, Pb and Mn) (Srichandan et al., 2019). Metal extraction takes place directly by electron supply (e.g. oxidation or reduction reactions) or indirectly by metabolic products of the microorganisms (inorganic or organic acids or excretion of complexing agents) (Auerbach et al., 2019). Bioleaching is a fully developed technology (TRL 9 for primary ores), and has been used at industrial level since 1960 for extraction of copper from sulphide ores. Currently, approximately 20% of the worldwide Cu is extracted using bioleaching (Latorre et al., 2016). Bioleaching can reduce contamination of wastes, contributing to their biostabilization and can be used to extract metals from ores or secondary wastes that are too low grade and therefore uneconomic to processing, using hydrometallurgical or pyrometallurgical methods.

3.2. Weaknesses

For further implementation of bioleaching as a technology for the circular economy, there is a need to improve process dissolution kinetics and metal leaching yields. Currently, bioleaching is slower than traditional extraction methods. Dissolution kinetics can be accelerated by optimisation of process parameters such as pre-treatments, reaction time, pH, temperature, mass transfer rate, nutrient requirements, pulp density, and particle size. Further developments in understanding the biotic factors controlling the inhibitory effects of pulp density on metal extraction are needed (Valix, 2017). Both single-stage, multistage, batch, and continuous stirred tank reactors can be developed and tested. To facilitate implementation on waste matrices, there is also a need to assess the process efficiency in larger, commercial relevant scale reactors, whilst focusing on process development and reactor design.

Fine-tuned processes assisted with microorganisms do exist, leading to the production of engineered inocula tailored to the target material and capable of high metal tolerance and improved selectivity towards the metals wanted as secondary resource (especially Cu, Co, Mn, V, Zn). The growing use of indigenous bacteria adapted to the environments instead of well-known strains from lab collections may overcome some of the limitations in terms of processing times (Pollmann et al., 2018). However, it will be challenging to use bioleaching for recovery of just one element, as further separation and purification techniques will be needed for circularity. The use of mixed culture instead of pure strain shows remarkable synergistic effects, especially against heavy metals that inhibit biomass growth, although pure cultures might demonstrate improved selectivity for the recovery of individual or groups of elements. The use of iron and sulphur (for acidophilic bioleaching) or organic sources (fungal and cyanogenic bioleaching) might increase bioleaching costs, as well as the need to add acid to keep the medium pH low (Srichandan et al., 2019). Adaptation of microorganisms to the waste materials can be critical, primarily due to heterogeneous feedstock composition, high buffering, and passivation effects. Alkaline wastes like MSWI ashes are unfavourable for bioleaching using acidophile cultures, so more data on alkaline bioleaching are needed other than fungal bioleaching, which showed limited performances in terms of metal yield, biosorption capacity, and volumes of biomass produced (Luo et al., 2019). Controlling the formation of inhibitory layers may overcome cell growth disruption and decrease metal extraction where a reasonable trade-off between microbial community succession and their energy types metabolisms can be maintained.

Regarding microbial development, there is also a need to better understand partnering of organisms and cell adaptation to the toxic effects of not only metals, but also toxic organic contaminants in the wastes (e.g. polychlorinated dibenzo-p-dioxins) (Valix, 2017). Metal separation from the bio-leachate also demands cost-effective and selective processes to recover metal ions. A major challenge is the recovery of low concentrations of metals from large volumes of dilute leachates (Pollmann et al., 2018).

3.3. Opportunities

Bioleaching has potential to recover metals from low-grade ores and wastes, but also to offset remediation (legacy sites) and operation costs by valorising wastes. This can also contribute to minimising the environmental impacts of raw materials extraction as potentially toxic elements are not discharged to the environment, but recovered for the circular economy. The importance of resource recovery in reducing carbon emissions could receive increased attention and should be leveraged to support the development of bioleaching. It can be expected that the growing demand for hi-tech elements driven by development and uptake of renewable energy technologies, will further promote research on bioleaching for metal recovery from wastes (Pollmann et al., 2018). Similarly, resource recovery will play a key role in securing the future availability of critical metals, and further investment in recovery technologies that have a high potential for implementation in multi-step processes for cost-effective mineral beneficiation, is likely.

Further opportunities reside in fine-tuned bioleaching to enhance selectivity to targeted metals, especially critical raw materials. Extension of bioleaching methods from two steps to three and four steps could mitigate the bacteriostatic effects of waste (Valix, 2017). Another area of development is accelerated carbonation and carbon sequestration in alkaline wastes using microorganisms (Mayes et al., 2018). Recent advances in microbial electrochemical technologies for energy production metal recovery are also promising (Huang et al., 2019; Pollmann et al., 2018). Similarly, reductive bioleaching of oxidised ores and urban biomining of electronic wastes (Sethurajan et al., 2018) can promote further research and implementation of bioleaching in municipal solid waste incineration residues.

3.4. Threats

Bioleaching efficacy can be compromised by the release of potentially toxic metals from wastes, which may affect the microbes used in bioleaching. Adaptation of microorganisms is critical for higher effectiveness of this biotechnology. The current lack of work practices, especially for wastes at pilot scale, may lead to poor reproducibility of metal recoveries in different matrices. Further research is needed to satisfactory cover more substrate materials and inocula. There is also a need to assess the downstream processing in case where excessive biomass is produced in the process.

The major threats for the implementation of bioleaching are statutory and financial factors, such as the volatility of markets and metal prices, currently low mineral extraction costs ("mineralogical barrier"), and the current low cost of landfill disposal; all of which are not favourable to resource recovery. Finally, the possibility of biological hazards needs accurate assessment at the prototype phase via standardised ecotoxicity tests that still have to be fully developed and should adapt to the proposed technologies.

4. Concluding remarks

Bioleaching allows recovery of critical resources from MSWI residues, such as fly ashes and bottom ashes, and in this paper, we have identified the Strengths, Weaknesses, Opportunities, and Threats associated with this biotechnology. Bioleaching is a promising approach for the recovery of metals, in particular critical raw materials, from wastes. However, further developments are still needed to enable sustainable and commercial application to residues from municipal solid waste incineration, to enable scale-up and demonstration of the commercial value. Advances in reactor design and demonstration at commercially relevant scales are critical to the adoption of this biotechnology. Techno-economic analysis, life cycle assessment (LCA), life cycle sustainability assessment (LCSA) are tools that can be used to establish and develop the application of bioleaching for resource recovery from wastes.

The full implementation of new technologies for resource recovery, such as bioleaching, needs an integrated policy and regulatory framework at all levels – local, regional, national, and international, not just scientific and technical advances. The need for regulatory, economic, and fiscal instruments to enforce and incentivise resource recovery is pressing. Some of these instruments might include providing a buffer against price volatility for recovered materials and metals; supporting markets in recyclates; whilst simultaneously investing in research and development and advancing technology readiness levels. Further investment in infrastructure and supply chains to enable resource recovery is also required.

Finally, good coverage of testing for suitable microorganisms and heterogeneous substrate materials is essential to fill the existing knowledge gaps and feasibility uncertainties for alkaline waste. Increasing environmental awareness, as well as limitations of traditional methods for complex materials with low metal content, will expand the development and application of bioleaching for primary ores. The potential amount of resources, in particular, critical raw materials such as metals, that can be recovered are relevant and can contribute to more sustainable waste management practices, whilst simultaneously avoiding unnecessary raw resource extraction and associated environmental impacts.

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Author contributions statement

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