JOHNSON MATTHEY
TECHNOLOGY REVIEW

www.technology.matthey.com

Johnson Matthey's international journal of research exploring science and technology in industrial applications

************Accepted Manuscript***********

This article is an accepted manuscript

It has been accepted for publication as a non-reviewed feature but has not yet been copyedited, house styled, proofread or typeset. The final published version may contain differences as a result of the above procedures

It will be published in the *Johnson Matthey Technology Review*

Please visit the website https://www.technology.matthey.com/ for Open Access to the article and the full issue once published

Johnson Matthey Technology Review
Johnson Matthey Plc
Orchard Road
Royston
SG8 5HE
UK
Tel +44 (0)1763 253 000
Email tech.review@matthey.com

<https://doi.org/10.1595/205651320X15935988177157>

<First page number: TBC>

BIORECOVER - New Bio-based Technologies for Recapture of Critical Raw Materials

Development of an innovative, sustainable and safe process from primary and secondary sources

By Annette Alcasabas

Johnson Matthey, 260 Cambridge Science Park, Cambridge CB4 0WE, UK

Felicity Massingberd-Mundy

Johnson Matthey, Blounts Ct Rd, Sonning Common, Reading RG4 9NH, UK

Barbara Breeze

Johnson Matthey, Blounts Ct Rd, Sonning Common, Reading RG4 9NH, UK

Maite Ruiz Pérez,

Fundación Centro Tecnológico de Investigación Multisectorial (CETIM), Parque Empresarial de Alvedro, calle H, 15180 Culleredo, A Coruña, Spain

Cristina Martínez García

Fundación Centro Tecnológico de Investigación Multisectorial (CETIM), Parque Empresarial de Alvedro, calle H, 15180 Culleredo, A Coruña, Spain

*Email: info@biorecover.eu

<ABSTRACT>

BIORECOVER brings together diverse expertise with the goal of developing a new sustainable and safe process, essentially based on biotechnology, for selective extraction of Critical Raw Materials (CRMs) rare earth elements, magnesium, and PGM.

The four-year EU H2020 project involves fourteen international partners from mining, microbiology, chemistry, engineering, metallurgy, sustainable process development, as well as CRM end-users. Starting from relevant unexploited secondary and primary sources of CRMs, BIORECOVER will develop and integrate three stages for CRM extraction – (1) Removal of major impurities present in raw materials and (2) Mobilisation of CRMs through use of microorganisms and (3) Development of specific technologies for recovering metals with high selectivity and purity that meet the quality requirements for reuse. Downstream processes will be developed and recovered metals will be assessed by end-users. Modelling and integration of the modular stages and economic and environmental assessment will be done to develop the most effective and sustainable process.

Introduction

Nowadays, the European Union (EU) depends on imports to supply critical raw materials (CRM) - materials established by the European Commission as raw materials of great importance for industry and the EU economy, with high risk associated with their supply and availability in the market.

Examples of CRM are the rare earth elements (REE - Sc, Y, La, Ce, Nd, etc), magnesium, and platinum group metals (PGM - Pt, Pd, Ru, Rh, Ir). The largest use of the 8,350 tonnes of REE is for catalysts (42%) followed by glass additives and over 90% of these are imported from China (1–3). In the same way, 85% of the 130,000 tonnes of magnesium annually consumed are imported from China (3, 4); the main uses being as magnesium casting alloys for transportation applications and aluminium alloys for packaging, transportation and construction (3). The EU supply of platinum is dominated by South Africa with around 70% of supply from the country alone (3, 5). PGM are primarily used in the production of catalysts for automotive and chemical industries and in electronic applications. With this strong reliance on CRM from outside the EU the development of innovative extraction processes is essential to extensively exploit raw material sources, primary and secondary, sourced within the EU.

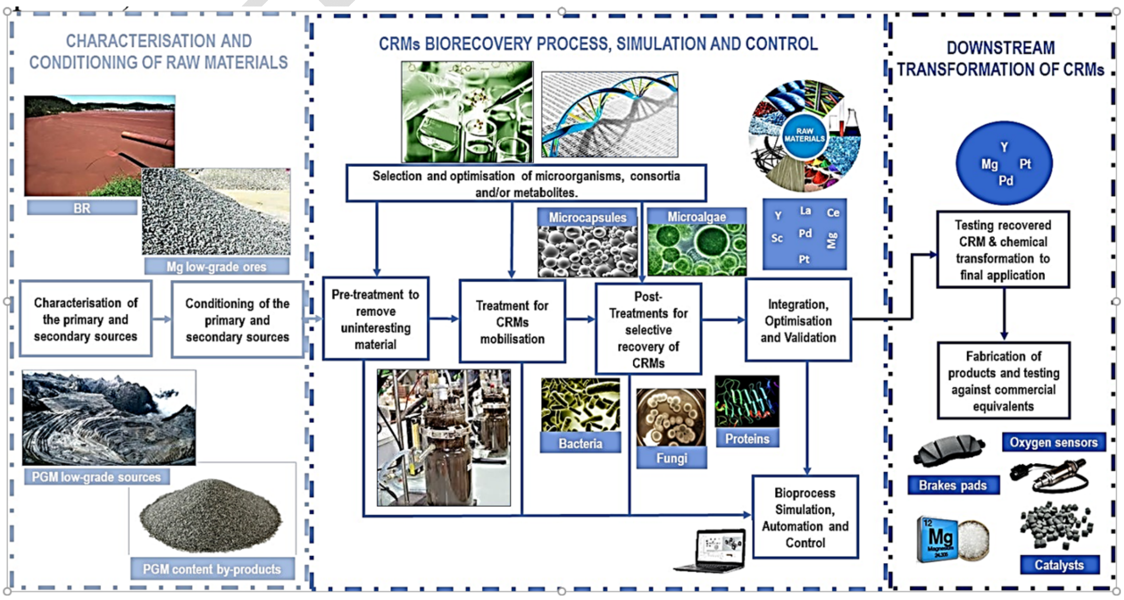
In this context, the BIORECOVER project aims to reduce the gap between the European supply and demand for CRM (REE, Mg and PGM) by providing innovative, flexible and versatile alternative processes based on modular and mainly bio-based technologies. The scientific advances in the field of biotechnology (bacteria, microalgae, fungi, proteins, etc.) will allow the exploitation of CRM inaccessible by conventional extraction methods.

The Biorecover Project

Project Aims and Approach

The BIORECOVER project aims to produce a suite of versatile and flexible recovery processes applicable in several conditions (pH, mineral complex, raw materials, etc.), which obtain high recovery yields (≥90%), selectivity (>95%) and purity (≥99%) and delivers both environmental sustainability and cost-efficiency in safe conditions. The BIORECOVER strategy is based on research, integration and optimisation of the following stages at laboratory scale: pre-treatment to remove major impurities in the raw materials, mobilisation of the target CRM into a bioleachate, and recovery of metals with high selectivity and purity. Selection and integration of the best technologies will be carried out (one route for each type of raw material), and the selected processes will be optimised and validated, producing samples for end-user testing assuring the product quality requirements for their reuse in different applications (Fig. 1).

Fig. 1



DOI:10.1595/205651320X15935988177157

To increase the efficiency and the sustainability of the BIORECOVER processes, valorisation of the by-products and wastes generated will be studied towards a Zero Liquid Discharge process. These BIORECOVER aims will be supported by applying tools such as interactive Life Cycle Analysis and Life Cycle Costing. Additionally, modelling of the overall process will be performed to develop a Decision Making Framework to maximise the performance. To obtain a competitive, secure, sustainable and publicly acceptable process, the project will be supported by Socio-Economic and Health and Safety analyses.

To achieve these goals, the BIORECOVER project has brought together an interdisciplinary consortium involving partners across the whole value chain from suppliers, scientific experts to the CRM end users, as well as two Small-to-Medium Enterprises specialised in dissemination, communication, exploitation and social issues (Table I).

Supply of raw materials

MYTILINEOS S.A., Metallurgy Business Unit (formerly known as Aluminium of Greece) is providing a REE-containing bauxite residue (BR) for the project. BR is the insoluble material generated during the extraction of alumina from bauxite ore using the Bayer process. When bauxite ore is treated with caustic soda, the aluminium hydroxides/oxides contained within are solubilised, leaving behind other bauxite oxides (mainly iron oxides, silica and titania) to form insoluble BR. The BR is washed then filterpressed to reduce storage volume and recover the alkaline solution (6). MYTILINEOS currently recycles ~10% of this residue as an additive for cement production, however the rest is stockpiled as a waste product. BR contains low amounts of some high value REE, such as scandium and yttrium, which are not currently recovered (7). BIORECOVER aims to recover these REE and, in doing so, reduce the build-up of and extract more value from the BR waste.

Magnesium-containing feeds are being supplied by Magnesitas de Navarra (MAGNA). Magnesite (magnesium carbonate) is mined, crushed, ground and enriched. Then the carbonate is either sintered at around 1800 °C to produce magnesite sinter for the steel industry or calcined at around 1300 °C to produce reactive magnesium oxide, used in agriculture, livestock farming and other industrial and chemical technologies (8). The waste streams of low-grade mineral and calcination by-products (MgW) still contain some Mg, which is currently not recovered. The low-grade mineral is deposited in mining dumps, whilst the calcination by-products are used in different industrial and environmental applications due their small particle size and basifying characteristics.

Johnson Matthey (JM) is supplying low-grade residues from its secondary PGM refineries. The feed intake is a mix of end-of-life PGM products and process residues, from spent catalysts to electronics and jewellery scrap. There are four main stages in the refinery process. In the smelting step, PGM-containing bullions are produced, alongside a non-metallic stream which goes to second uses such as aggregates. The PGM-containing bullions then undergo chemical leaching processes to produce PGM solutions. In chemical separations, the PGM solutions are converted into separate PGM salts or high purity fine metal powder. These are then transformed into application-ready products, such as catalytic converters, which are fed back into the refinery at end-of-life (9). During the refining stages, lost material containing low levels of PGM is recovered and fed back into the smelting stage. This recovery is a

DOI:10.1595/205651320X15935988177157

highly energy intensive process relative to the low levels of PGM present and so recovering the precious metal through a bio-process would be more sustainable and lower cost.

The final raw material is PGM-containing low grade material and concentrates which the University of the Witwatersrand (UWITS) is sourcing from Anglo American Platinum in South Africa.

The BIORECOVER technologies

Biometallurgy is a proven green and low-cost technology for the exploitation of metals through the application of different biocatalysts (microorganisms and metabolites) (10). These biocatalysts interact with metals by selectively concentrating or mobilising them. One crucial limitation of biometallurgy is the long retention times that are currently required. To address this, BIORECOVER will identify and develop new biocatalysts with improved performance. This approach, using microorganisms indigenous to mining and CRM storage sites, will assure fewer ecological distortions and less time consumption for adaptation. In terms of leaching efficiency, native strains usually achieve higher cell density and greater metal extraction rates than exogenous microbes. In addition, use of the following state-of-the-art technologies will facilitate the development of microbial consortia more competent for biometallurgy (11).

- metagenomics (sequencing of genomes from environmental samples)
- metatranscriptomics (identification of expressed transcripts)
- proteomics (identification and quantification of proteins)
- metabolomics (measurement of cellular metabolites)

- interactomics (understanding cellular interactions)

Another innovative approach to improve the biomining processes is the immobilisation of microorganisms onto supports that will enable the continuous supply of nutrients without competition, increase biomass, give protection from environmental stress, and provide more control at a lower cost (12).

The first two biological steps in CRM recovery are pre-treatment and CRM mobilisation. In both steps, BIORECOVER will isolate and cultivate microbial populations present in the feed. These would be expected to be naturally metal resistant and possess other valuable traits. BIORECOVER will use metagenomics and metatranscriptomics to identify and characterise these samples, as well as isolates from existing culture collections, that have the ability to remove impurities (for pre-treatment) and/or leach CRM from samples (for CRM mobilisation).

For pre-treatment, University of Copenhagen (UCPH) and University of Coimbra (UC) will screen microbial communities, present in either the unconditioned raw material or the UC culture collection, for the ability to remove impurities (Fe, Al, Ca and Ti for BR; Silicon, Fe and $CaCO_3$ for MgW). For PGM-containing material, UC will use selected mesophilic and thermophilic microbes and UWITS will isolate iron and sulfur-oxidising bacteria to test removal of Cu, Ni, Co, Zn and Fe from PGM-containing JM refinery residues and Anglo American Platinum mining waste, respectively.

For CRM mobilisation, Linnaeus University (LNU) will screen both indigenous microbial communities as well as fungal cultures known to excrete organic acids for the ability to mobilise REE in BR samples. LNU will also screen organisms in MgW for the ability to leach Mg and in JM low-grade residues for the ability to leach PGM.

Fundación Centro Tecnológico de Investigación Multisectorial (CETIM) will optimise

DOI:10.1595/205651320X15935988177157

CRM mobilisation conditions for microorganisms selected for BR and MgW. UWITS will sample soil around PGM deposits to isolate cyanide-producing bacteria that can mobilise PGM.

For both pre-treatment and CRM mobilisation, the partners will perform further screening, testing relevant conditions such as co-cultivation for synergistic effects, and testing with different CRM concentrations to optimise activity.

In the third step, CRM recovery, BIORECOVER will develop five different sustainable technologies to bind CRM. Técnicas Reunidas (TR) will test and develop selective reusable polymeric microcapsules with "almost zero" extractant consumption to recover a wide range of REE and Pt. ALGAENERGY will cultivate and screen different microalgae species and develop microalgal-based biosorbents to recover mainly Y, Mg, Pt, and Pd. UC will screen planktonic cells that produce siderophores and immobilised systems to develop an adsorption process for Y and PGM. CETIM will screen fungi with known Mg-binding activity to develop a biotransformation process to make Mg nanoparticles. JM will design and synthesise different proteins and peptides to develop protein products that can adsorb Mg and Pt.

For all three steps, data from all groups will be collected by University of Cape Town's Centre for Bioprocess Engineering Research (CeBER), who will develop kinetic models, that will be valuable in process optimisation. This will facilitate process improvement towards achieving a target recovery rate (>90%), selectivity (>95%) and purity (>99%).

In the second half of the project the best technology for each step will be selected, integrated into a complete process and scaled-up to 5L bioreactors and/or columns. Along with the process modelling this will successfully optimise and validate the

DOI:10.1595/205651320X15935988177157

BIORECOVER strategy for the different CRM feeds. A technical, environmental, and economic assessment of the selected process for each feedstock will be conducted to improve the performance and to facilitate further replicability and scaling up of the BIORECOVER technology.

Project Outputs

The CRM recovered through the BIORECOVER processes will be tested for end use by industrial project partners.

Francisco Albero S.A.U. (FAE) will test the application of the recovered Y and Pt for brake pads and oxygen sensors, respectively. FAE fabricate brake pads by tape casting then sintering advanced ceramic slurries. Y is added to the slurries to reduce the sintering temperature. FAE also produce oxygen sensors made of zirconia for exhaust gas monitoring. Conductive parts of the oxygen sensors are fabricated by screen-printing Pt inks on ceramic substrates.

The use of the recovered Pt, Pd, and Ir for commercial catalysts will be tested by JM. Catalysts will be prepared and their catalytic activity will be tested on a range of reactions, including carbon monoxide and hydrocarbon oxidation, selective hydrogenation, selective nitro reductions, and carbon-carbon bond forming reactions.

MAGNA will characterise the recovered Mg nanoparticles and compare this with Mg obtained through conventional technologies to assess their suitability for commercial applications such as agricultural fertilisers.

The dissemination of the project's achievements to a wide range of stakeholders (policy makers, industry groups, potential markets, the academic community, etc.) will be key for the successful exploitation of the project. Diffusion actions will include

DOI:10.1595/205651320X15935988177157

conferences, seminars, workshops, scientific publications as well as engagement with other relevant projects on CRM recovery. Finally, a strategic plan to exploit the results generated during and after the end of the project will be accomplished in terms of business models and intellectual property rights strategy.

For more information about the BIORECOVER project please visit the website: **https://biorecover.eu/**

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 821096. The authors would like to thank and acknowledge the consortium partners for their input into the preparation of this manuscript.

References

1. CRM Alliance, 'Light Rare Earths', 'CRM Alliance Crit. Raw Mater', 2016 LINK https://www.crmalliance.eu/lrees

2. CRM Alliance, 'Heavy Rare Earths', 'CRM Alliance Crit. Raw Mater', 2016 LINK https://www.crmalliance.eu/hrees

3. Deloitte Sustainability, British Geological Survey, Bureau de Recherches Géologiques et Minières and Netherlands Organisation for Applied Scientific Research, 'Study on the Review of the List of Critical Raw Materials Critical Raw Materials Factsheets' European Commission, 2017

4. CRM Alliance, 'Magnesium', 'CRM Alliance Crit. Raw Mater', 2016 LINK https://www.crmalliance.eu/magnesium

5. CRM Alliance, 'PGMs', 'CRM Alliance Crit. Raw Mater', 2016 LINK

https://www.crmalliance.eu/pgms

6. A. Tabereaux, *Light Met. Age*, 2019, 77, (1), 54

7. E. Balomenos, P. Davris, Y. Pontikes, D. Panias and A. Delipaltas, 'Bauxite Residue Handling Practice and Valorisation Research in Aluminium of Greece', 2nd International Bauxite Residue Valorisation and Best Practices Conference, Athens, Greece, 7^{th}-10^{th} May, 2018.

8. Magnesitas de Navarra, 'How We Work' LINK

https://www.magnesitasnavarras.es/en/magnesite-products/how-we-work/

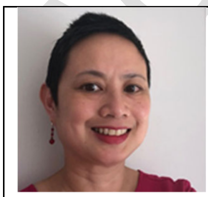
9. Johnson Matthey, 'PGM Refining' LINK https://matthey.com/en/products-and-services/precious-metal-products/pgm-refining

10. S. Ilyas and M. Kim, *J. Chem. Technol. Biotechnol.*, 2018, **93**, (2), 320

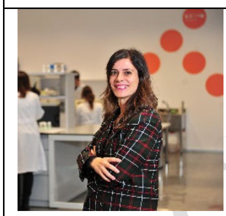
11. L. Valenzuela, A. Chi, S. Beard, A. Orell, N. Guiliani, J. Shabanowitz, D. F. Hunt and C. A. Jerez, *Biotechnol. Adv.*, 2006, **24**, (2), 197

12. R. Branco, T. Sousa, A. P. Piedade and P. V. Morais, *Chemosphere*, 2016, **146**, 330

The Authors

	Dr Annette Alcasabas is a Lead Scientist at the Biotechnology Department of Johnson Matthey. She has a background in microbial genetics and worked in industrial synthetic biology prior to joining JM in 2016. At JM, she is responsible for the molecular biology workflow used in commercial protein production and protein engineering. Annette is also part of a team that is exploring new opportunities and applications for biotechnology.

DOI:10.1595/205651320X15935988177157

	Felicity Massingberd-Mundy is a research scientist in the Recycling and Separations Technology department at Johnson Matthey, Sonning Common, UK. She graduated with an MChem from the University of Oxford in 2019, having conducted her final year research project in the New Applications group at JMTC Sonning. Her current research focuses on CRM recycling – specifically PGM and battery materials recycling.
	Dr Barbara Breeze is a Senior Principal Scientist in the Recycling and Separations Technology department at Johnson Matthey. She has experience of new process research and development for the recovery of critical metals from the end of life products, with a particular focus on battery materials recycling and Platinum Group Metals recovery.
	Dr Maite Ruiz is a Senior Researcher in the ECO BIO technologies department at Fundación Centro Tecnológico de Investigación Multisectorial (CETIM) in A Coruña (Spain). She has experience of recovery processes of CRM, valuable metals and bioactives from different matrices (e.g. Waste Electric and Electronic Equipment – WEEE, food by-products, etc.), with a special focus on bio-based technologies.
	Dr Cristina Martínez García is the Head of the R&D Eco Bio Technologies Department at CETIM, Cristina Martínez holds a PhD, Master Degree in Environmental Science and Technology as well as Degree in Chemistry at the University of A Coruña (Spain). She has been involved in the development of several national and international R&D projects focused on the development of new technologies in the area of circular economy: resources recovery from organic and inorganic wastes such as wastewater, sludge, minerals, by-products of animal and vegetable origin, etc to obtain high value commercial compounds.

DOI:10.1595/205651320X15935988177157

<Tables>

Table I

BIORECOVER consortium description. Raw materials characterisation and supply (brown); Recovery process research (green); End-users (orange); Dissemination, communication, exploitation & environmental and social issues(blue).

Partner	Country	Type of entity	Role			
Mytilineos Anonimi Etairia-Omilos Epicheiriseon (MYTILINEOS)	Greece	LE				
Magnesitas de Navarra (MAGNA)	Spain	LE				
University of Witwatersrand (UWITS)	South Africa	RTO				
Johnson Matthey (JM)	UK	LE				
University of Copenhagen (UCPH)	Denmark	RTO				
University of Coimbra (UC)	Portugal	RTO				
Linnaeus University (LNU)	Sweden	RTO				
Fundación Centro Tecnológico de Investigación Multisectorial (CETIM). Coordinator	Spain	RTO				
University of Cape Town's Centre for Bioprocess Engineering Research (CeBER)	South Africa	RTO				
Técnicas Reunidas (TR)	Spain	LE				
Algaenergy	Spain	SME				
Francisco Albero (FAE)	Spain	LE				
Vertech	France	SME				
LGI	France	SME				

<Figure captions>

Fig. 1. The flow-scheme of BIORECOVER

DOI:10.1595/205651320X15935988177157