Mine Closure 2025 – S Knutsson, AB Fourie & M Tibbett (eds)

doi:10.36487/ACG_repo/2515_104

Bioderived element resource separation technology for waste processing

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Abstract

New methods for selective recovery of around USD 3.4 trillion worth of critical resources left in mining-influenced water are needed to enable improved waste valorisation and better environmental outcomes. Biological solutions for metal and mineral extraction have evolved over millions of years as they are essential resources for living organisms. These are many of the same critical resources that are required for manufacturing the technologies of the future. Membrane separation mechanisms used by living organisms to manage metal and mineral nutrient uptake and distribution are therefore being leveraged to develop next-generation mining biotechnologies that enable the recovery of critical materials from wastes. Research into mechanisms that diverse plant species use for selective resource separation has led to the development of the bioderived element resource separation technology (BERST) system. BERST is a modular biomimetic membrane system designed to extract permeates of high-purity metals, minerals and clean water from complex mining-influenced feed solutions. The BERST membrane system incorporates collections of bioengineered, highly selective, pore-forming structures inspired by nature and optimised for stability and performance that enable targeted and selective separation of valuable metals and minerals from wastes. Demonstration of selective metal recovery using BERST is at the laboratory-scale prototype testing stage. Deployment of systems like BERST that enable mining-influenced waters to be separated into high-purity metal, mineral and clean water resources align with the concept of 'economic rehabilitation', where the residual value in mining-influenced water is harnessed to improve the social and environmental outcomes of mine closure and operations. BERST is expected to contribute to enabling sustainable management of mining-influenced waters, reducing environmental impacts and supporting circular practices in the mining industry.

Keywords: *membrane, separation, bioengineering, mining-influenced water, valorisation, remediation*

1 Introduction

Building a sustainable future depends on careful management of the critical resources required for the green and clean energy transition. Mining operations deliver these critical resources but also generate substantial volumes of waste and have a significant environmental footprint. With operations often spanning decades, mining companies are entrusted with the stewardship of the land they mine, including mitigation of environmental impacts and facilitating its transition to productive uses after mine closure. However, previous studies have reported tens of thousands of inactive and unrehabilitated mine sites in Australia, with only 15 examples of repurposed mined land (Werner et al. 2020). With approximately 240 Australian mines projected to close by 2040, and associated closure and remediation costs estimated at AUD 4–8 billion annually (CSIRO 2023), there is an immediate need for innovative and effective waste management and rehabilitation strategies.

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The management of mining-influenced waste is one of the most complex and intensive aspects of mine closure. Poorly managed waste can create environmental and safety risks and ongoing liabilities long after mining operations have ended. For example, acid mine drainage (AMD) impacts hundreds of thousands of kilometres of freshwater waterways, making reservoirs of freshwater unusable and prompting the United Nations to rank AMD as second highest on its list of global environmental concerns, after climate change (Daraz et al. 2023). Best practices in mine closure now recognise that basic compliance, including the management of mine waste like AMD, is not sufficient to achieve optimal environmental and social outcomes. Therefore, there is a growing emphasis on proactive strategies that go beyond regulatory requirements to create long-term value and positive legacies.

The concept of 'economic rehabilitation', whereby the residual value in mining waste is leveraged to improve the social and environmental outcomes of mine closure and operations, has gained interest. Mining typically recovers only 70–80% of valuable materials from deposits, leaving 20–30% in tailings and waste (Mining Weekly 2024). The value of the critical resources currently trapped in mining waste worldwide is estimated at USD 3.4 trillion (Minerals Research Institute of Western Australia 2024). Realising the untapped potential of mining-influenced waters transforms them from a liability into an asset, creating new revenue streams, reducing closure costs and unlocking additional resources. Advancements in processing technologies are making it increasingly feasible to extract valuable materials from mining-influenced waters. Interdisciplinary research and development spanning chemical, biological, environmental and material sciences fields are relevant to addressing the technical challenges of extracting value from mine waste while creating economic opportunities. In biological research, novel approaches have leveraged microorganisms, plants and ecological processes to extract value from mining waste while mitigating pollution.

Living organisms have evolved sophisticated mechanisms for metal and mineral extraction over billions of years, driven by the essential role these elements play in sustaining life (Merchant 2010). Metals such as iron, zinc and copper serve as cofactors in critical metabolic processes – from oxygen transport in haemoglobin to enzymatic reactions in cellular energy production. The fundamental biological need for metals for specific functions has led to the evolution of highly specialised structures within living cells that are able to distinguish between metal elements. The 3.8-billion-year research and development program encoded in biological systems through the evolution of life on Earth offers sustainable solutions for modern challenges in metal recovery, recycling and environmental management (Hunter 2008). The novel Bioderived Element Resource Separation Technology (BERST) biomimetic membrane we are developing aims to deliver sustainable solutions towards harvesting untapped critical resources for re-use from waste water sources such as mine tailing ponds and AMD. Here we review the current state-of-the-art in biomimetic membranes, the advantages BERST can provide over currently used technologies and processes for metal extraction and recovery from wastes, and the potential impact that large-scale adoption of this technology could have on the dynamics of mine closure into the future.

2 Drawing inspiration from selective membrane separation in nature

2.1 Membrane separation is critical to life on Earth

Biological membranes underpin all life on Earth because they enable the separation of different chemistry on the inside of cells relative to the outside (Deamer 2016). This chemical separation supports the maintenance of an electrical potential difference across the membrane and allows cells to concentrate and manage the key resources needed to undertake the chemical reactions required for life (Lane & Martin 2012). Precise control of what molecules are able to pass across cell membranes is therefore critically important. The movement of many molecules across membranes is facilitated by genetically encoded membrane integral protein structures called membrane transport proteins. Membrane transport protein structures span across biological membranes, forming highly selective pathways through which molecules can pass.

There are many thousands of known membrane transport proteins across the kingdoms of life (Ren et al. 2007), each with distinct structural and functional characteristics that enable them to perform their essential roles in maintaining cellular homeostasis. For example, previous studies have described 71,659 transport proteins and 4,790 outer membrane channels assigned to 183 types of protein families across 248 organisms (Ren et al. 2007). The selectivity of membrane proteins is conferred by their 3D structure, dynamic movements and the biochemical features of the amino acids that comprise them, meaning that many are able to differentiate between molecules based on the charge number, polarity, size and molecular mass of the molecules (Drew & Boudker 2016). Because minerals and metals are essential micronutrients for life, membrane transport proteins that enable the selective passage of minerals and metals across the membrane have evolved. The selectivity of these membrane protein structures represents untapped potential for selective metal extraction and processing.

2.2 Tapping into the potential of separation mechanisms evolved in plants

Plants are exceptional targets for inspiring the development of biotechnologies or bio-based solutions to industry challenges. The scale of membrane separation functions performed by plants exceeds the scale achieved by any other form of life on Earth. Plants contribute critical separation functions in natural ecosystems, including filtering around half the global rainfall, generating ~85% of oxygen, capturing ~33% of atmospheric carbon dioxide, absorbing solar radiation and delivering food, feed, fibre and fuel (Arsic et al. 2024). The critical ecosystem services undertaken by plants involve processes that are underpinned by the highly selective transport of solutes across membranes (De Rosa et al. 2023).

The magnitude of membrane separation functions occurring in nature can be considered in terms of the biomass resources generated by these processes, and the diversity in the genetically encoded selective transport mechanisms that enable precision separation across membranes. Plants contribute the greatest biomass on Earth relative to organisms from other kingdoms, accounting for approximately 82% of Earth's total living biomass (Bar-On et al. 2018; Figure 1). The magnitude of the various resources separated by plants on Earth demonstrates their capability to deliver efficient and productive membrane separation at scale because all of the raw resources that comprise plant biomass, such as carbon dioxide, water, nutrients, metals and minerals, have been sourced from their surrounding environments, separated and utilised via specialised membrane-enabled processes (Arsic et al. 2024).

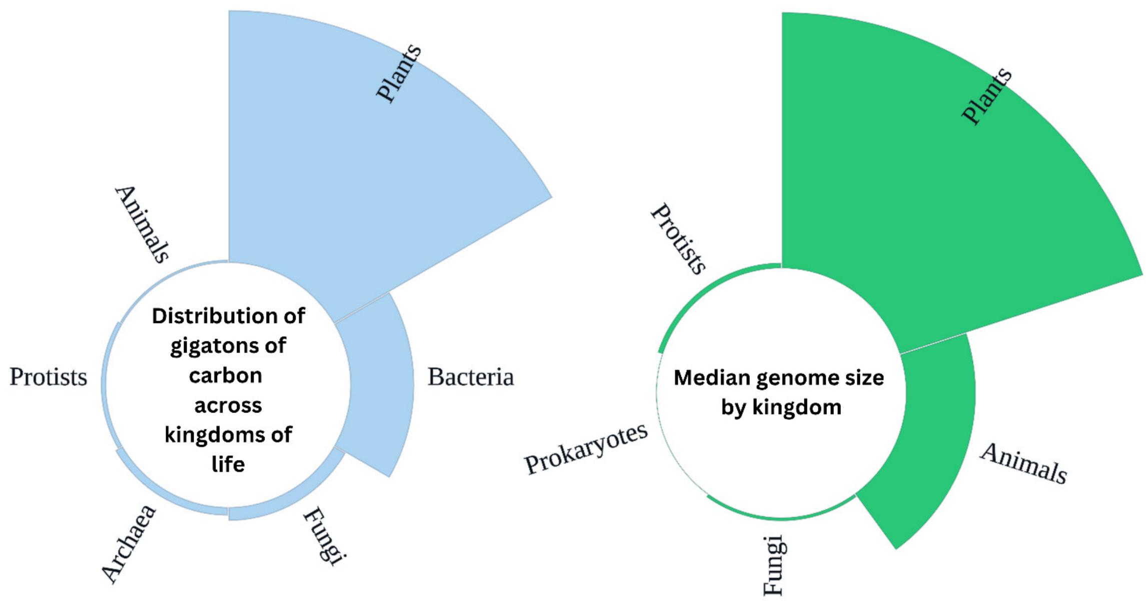

Figure 1 The relative distribution of gigatons of carbon and median genome size across kingdoms of life, where the massive biomass of land plants gives them mass dominance (data from Bar-On et al. 2018). Biomass (gigatons carbon): plants, 450; bacteria, 70; fungi, 12; archaea, 7; protists, 4; animals, 2. Plants have the largest median genome sizes among life forms (data from He et al. 2024; Hotaling et al. 2021). Median genomes (megabases): plants, 5,958; animals, 1,020; fungi, 35; prokaryotes, 3.2, protists, 59.5

The mass and diversity of plants enables ecosystems to support diversity in other forms of life because different types of plants deliver different types of biochemical resources. Plants' extraction of nutrients and metals from soils, and partitioning of those nutrients and metals within their biomass, directly influences the nutrition of animals, including humans, that consume plant products. For example, manipulation of plant mechanisms that influence iron and zinc accumulation in wheat grain enabled a threefold increase in iron and zinc in flour from the modified wheat plants; an achievement that was delivered to address human dietary deficiencies (Harrington et al. 2022). This demonstrates that engineering plant metal transport processes to create biotechnological innovations is relevant as a pathway to optimising resource management for outcomes that benefit communities.

Plant adaptation to challenging environments draws on genetic diversity to evolve solutions for coping with various stressors (Figure 2) influencing plant genome size and diversity, relative to each of the other kingdoms of life (Pellicer et al. 2018). Plant genomic size and diversity has primarily occurred through whole-genome duplications and DNA expansions (Hotaling et al. 2021; He et al. 2024; Figure 1) leading to unique genomic complexities and contexts. There was selective pressure driving plants to increase and diversify their genomes because greater genome size and diversity provide greater raw genetic material for adaptive evolution, such as novel traits for stress tolerance or reproductive strategies (Pellicer et al. 2018).

The high propensity for plant genome duplication and expansion events has facilitated their adaptability to diverse environments, repurposing and tailoring gene function to thrive in distinct ecosystems and diverse soil compositions. The genomic diversity of plants includes variations in genome ploidy and protein-coding gene-family duplications, with some plant species having up to an estimated 40,000 protein-encoding genes (Sterck et al. 2007). Gene-family duplication is often associated with sub-functionalisation of gene-families (Fang et al. 2022). Sub-functionalisation refers to an evolutionary process where duplicated genes encoding the same protein accumulate mutations over time. This allows the original protein to evolve new, specialised functions in specific plant lineages, shaped by their divergent ecological or developmental needs (Flagel & Wendel 2009; Panchy et al. 2016). The unique genomic diversity of plants offers significant advantages over other kingdoms of life in terms of their potential to encode useful mechanisms.

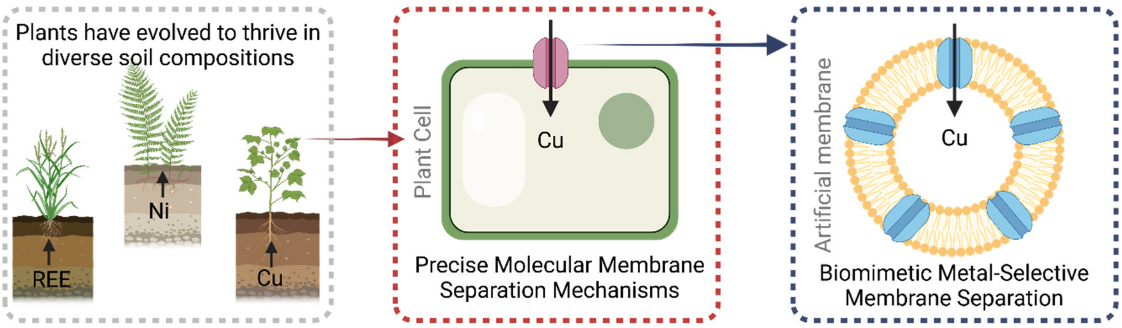

Figure 2 Harnessing the function of diverse membrane separation mechanisms evolved in plants to develop novel biomimetic metal-selective technologies. Membrane-embedded selective pore structures naturally occurring in plants enable separation of distinct chemistries across cell membranes (De Rosa et al. 2023). These selective separation mechanisms can be further engineered with enhanced function and stability for biomimetic metal-selective membrane technologies for industrial applications. Purple pore structure – selective membrane transport protein found in nature; blue pore structure – engineered selective membrane transport protein; Ni – nickel; REE – rare earth elements; Cu – copper

Global heterogeneity in soil geochemistry, including the distribution and abundance of metal elements, means that plants have been exposed, and challenged, to adapt to survive in different soil solution compositions (De Rosa et al. 2023). Metal-selective transport proteins constitute an important adaptive mechanism because they enable the uptake and distribution of critical metal nutrients across plant tissues, as well as the management or compartmentalisation of metals that may be toxic or present at toxic concentrations. The selective pressure exerted on plants exposed to metal-rich soil geochemistry has also led to the evolution of plants known to hyperaccumulate metals in their living tissues to many hundreds or even thousands of times greater than is normal for most other plant species (Krämer 2010; Reeves et al. 2017). For example, there are copper and rare earth element (REE) tolerant plant species that can accumulate in the order 1,000 $mg.Kg^{-1}$ of these valuable elements (Yuan et al. 2018; Widmer & Norgrove 2023; Wang et al. 2024a). The ability for some plant species to hyperaccumulate metals suggests they possess unique membrane transport mechanisms that have improved selective functions compared to those in non-hyperaccumulator plant species. These mechanisms might include transporters such as *Medicago truncatula* copper transporter, MtCOPT1 (Senovilla et al. 2018), or natural resistance-associated macrophage proteins for REE uptake (Zheng et al. 2023), or channels such as subsets of membrane intrinsic proteins (McGaughey et al. 2025). The protein structures nature has evolved to separate critical resources are relevant as inspiration for designing biotechnological solutions for critical resource separation.

3 Biomimetic membranes: current state and opportunities

3.1 Installing parts from nature into manufactured membranes

Artificial membrane manufacture typically involves synthetic chemical and biochemical approaches. Advances in membrane fabrication and function are relevant to biomedical and healthcare technologies, energy technologies, environmental remediation, chemical and industrial processes, and materials science innovation. Artificial membranes can be made of components like lipids and block copolymers that spontaneously organise into membrane structures. Block copolymers are polymers made of distinct segments of monomers arranged in the main chain, where each segment consists of repeating monomer units (Quirk et al. 1996).

The successful separation of molecules across a membrane depends on several critical factors, including the molecular cutoff size of the membrane, its morphological structure and its chemical affinity for specific compounds (Osman et al. 2024). Membrane manufacturing processes can incorporate a range of methods and types of materials that influence membrane properties and functionality (Kerr-Phillips et al. 2022). Some examples of fabrication processes include:

- Phase inversion: polymer solutions undergo phase separation in a coagulation bath, creating a porous, solid membrane with an asymmetric structure where a polymer-rich phase forms the scaffold and a polymer-lean phase creates the porous network; polymers can be spun into a coagulation bath to form hollow fibres through phase inversion
- Electrospinning: a strong electric field is applied to charged polymer solutions to make flexible and continuous microfibres or nanofibres. Fibre thickness, pore size and surface porosity can be controlled by adjusting the electrospinning parameters
- Interfacial polymerisation: a porous support membrane is treated with reactive solutions that form a thin polymer layer at the interface. Thin-film composites are created by adding thin layers on porous supports, and for molecular layer deposition this involves depositing molecular-scale layers.

Synthetic separation membranes are limited by the seemingly universal compromise between permeability and selectivity; that is, highly permeable membranes lack selectivity and vice versa (Park et al. 2017; Lim et al. 2022). Conventional membrane fabrication techniques currently do not support the molecular-level design that is required for achieving single solute selectivity. Biological membranes do not share these limitations, achieving both high permeability and high selectivity in combination. This is because biological membranes can incorporate and regulate collections of membrane proteins that vary in their permeability and selectivity, enabling dynamic adjustment of these factors to support growth, development and adaptation to environmental conditions (Tyerman et al. 2021; Byrt et al. 2023). The unique functionality of biological membranes is inspiring design approaches for improving membrane performance, leading to the development of biomimetic membranes (Hélix-Nielsen 2018).

Biomimetic membranes can directly incorporate biological elements or otherwise use concepts, ideas or inspiration from biological systems. In general, biomimetic membrane developments and approaches can be categorised as: (i) hybrid membranes that incorporate biological membrane proteins reconstituted into synthetic supporting membranes; or (ii) synthetic membranes that incorporate functional molecules that mimic the function of natural membrane proteins or form artificial channels in the membrane structure (Shen et al. 2014). These approaches create nanopores, biological or synthetic, in the membrane that have specific size, shape, charge, hydrophobicity and affinity parameters which can facilitate or enhance the selective transport of certain molecules (Lindahl & Sansom 2008). An example of a hybrid biomimetic technology is the Oxford Nanopore MinION, which contains engineered protein channel nanopores embedded in an artificial electrically resistant membrane. The nanopores facilitate the sequencing of DNA, RNA and, more recently, proteins by detecting changes in ionic current as molecules pass through the pore (Dorey & Howorka 2024; Lu et al. 2025). For synthetic biomimetic membranes, carbon nanotube channels have been developed to mimic biological water channel structures that have high permeability (1936 ± 123 μm s^{-1}) and ion selectivity (complete rejection of salt ions) (Liu et al. 2021). These examples indicate that, although in its infancy, biomimetic membranes are a promising area for research and development.

Research and development activities that involve integration of biological components into manufactured membranes aim to take advantage of the specific separation function (such as transport selectivity and efficiency) of the structures that have evolved over millions of years of selective pressure. While biomimetic membrane technologies that incorporate biologically derived structures are commercially available and are being used across a broad range of applications, possibly the most mature in the market are water-selective biomimetic membranes used in water treatment applications.

3.2 Biomimetic membranes for water filtration

Biomimetic water-selective membranes have been developed where biological water channel proteins are reconstituted into synthetic membrane materials, or where biological water-selective structures are mimicked by synthetic structures termed artificial water channels (Lim et al. 2022). The research teams which developed biomimetic membranes that incorporate biological protein structures chose water-selective proteins from the aquaporin protein family to improve membrane water selectivity and permeability (Zhao et al. 2012; Li et al. 2015). In cellular membranes, water-selective aquaporin proteins form a cylindrical channel pore to facilitate water transport. In addition to enabling efficient water transport across membranes, aquaporins in plants have evolved to facilitate efficient separation of other key plant solutes, including metals and minerals (Tyerman et al. 2021). In living organisms, water-selective aquaporins are critical for maintaining water homeostasis and the turgor pressure of cells; and in plants, they enable water uptake from the soil environment and the regulation of water flux between tissues and cell compartments. The structure of water-selective aquaporins enables water molecules to permeate as single-file chains, with single-molecule selectivity and a permeance of 1.6×10^{6} L $m^{-2}h^{-1}bar^{-1}$ per aquaporin (Park et al. 2017). Water-selective aquaporin structures exclude other solutes by having a narrow channel geometry that enables steric hindrance to be exerted on the approach of non-water molecules to the constriction site and electrostatic repulsion due to an aromatic/arginine constriction site (Oliva et al. 2010). To maintain protein structure and function in an end-use separation membrane technology, aquaporins must be reconstituted in an amphiphilic environment similar to a biological cell membrane (Habel et al. 2015). The aquaporin biomimetic membranes currently available are fabricated from three primary components: aquaporin proteins, an amphiphilic membrane and a porous supporting structure. In these membranes, aquaporin proteins are embedded into a membrane-like structure formed by amphiphilic molecules, either lipids such as in biological systems, polymers or a combination of both lipids and polymers, and this structure is supported by a porous polymer substrate. The fabrication of aquaporin biomimetic membranes can be achieved by incorporation of aquaporin proteins into a simple planar bilayer, or into spherical membrane structures called vesicles.

Protein incorporation into manufactured membranes can be achieved during membrane bilayer assembly where cycles of exposure of the membrane substrate to solutions containing proteins are repeated, or by generating various membrane layers using spray, spin coating or solution dipping approaches. Examples of methods used for controlling the incorporation of proteins into manufactured membranes include vesicle adsorption, chemical crosslinking, interfacial polymerisation, magnetic-aided adsorption and electrokinetic interaction (Fuwad et al. 2024). The aquaporin-embedded membranes are then formed or deposited on a solid supporting substrate.

State-of-the-art water-selective aquaporin-embedded biomimetic separation membranes are fabricated into hollow fibre systems. Hollow fibre filters have an outer shell and compartments separated by selectively permeable membranes and non-permeable barriers to enable partitioning of feed and permeate solutions. In hollow fibre systems the selectively permeable aquaporin-embedded membrane layer coats the interior surface, or lumen side, of the porous hollow fibre supporting structure where the inner diameter of the fibres is ~195 µm and the wall thickness is ~25 µm. Feed solution enters the lumen, or inner volume, of the hollow fibre and water is selectively separated across the aquaporin-embedded membrane to the outer side of the fibre to the draw solution. The architecture of hollow fibre systems enables a high membrane surface area for a relatively small module size. These systems typically include tightly packed fibres where the inner diameter of the fibre may be in the order of 0.2 mm, and the packing density of the fibres may be in the order of 1,600 m^2 of membrane surface area within every cubic metre of module (Abid et al. 2023). Hollow fibre modules containing water-selective aquaporins that are 70 mm in diameter and 300 mm long, and which contain a 2.3 m^2 membrane active area (Sterlitech 2017), have been retailed. Modules that are 390 mm long and 200 mm in diameter with an active surface area of 13.8 m^2 have also been developed (Sterlitech 2019).

The barriers between compartments in hollow fibre systems can enable two-phase flow or countercurrent flow, an arrangement that allows for efficient exchange of a property, like solutes. Countercurrent flow is where working fluids flow in opposite directions but where there can be transfer of a property between the fluids. The term ‘countercurrent exchange’ refers to the process of maximising the exchange of a property between two fluids by using countercurrent flow. In nature, an example of countercurrent flow can be found in the nephron loop in kidneys, where it is used to concentrate urine by creating a solute concentration gradient, and in fish gills, where it allows for efficient oxygen uptake from water and carbon dioxide release (Sands & Layton 2014; Sackville et al. 2024).

Hollow fibre systems can be used for forward or reverse osmosis separation. Forward osmosis is where natural osmotic pressure drives water flow across a semi-permeable membrane, whereas reverse osmosis uses hydraulic pressure to force solutes through a membrane. For water filtration, energy efficiency gains have been made by using natural osmotic pressure gradients formed due to differences in the concentration and osmotic potential of system feed and draw solutions between membrane-bound compartments. For these applications, a low-osmotic solution like waste water would be input as a feed solution and a high-osmotic solution, like concentrated sodium chloride, would be used as a draw solution. The output streams from hollow fibre filters can include a concentrated feed that retains > 95% of the original solutes and a diluted draw which contains purified water and minimal salt.

Embedding of water-selective aquaporin proteins in hollow fibre membrane filters has enabled gains in separation efficiency of clean water from complex mixtures relative to systems without aquaporins (Li et al. 2015). Early proof-of-concept studies for aquaporin biomimetic membranes, using the bacterial aquaporin AqpZ, reported water permeability up to two orders of magnitude higher than the existing desalination membranes at the time and a selectivity approaching 100% (Kumar et al. 2007).

Projects that involve scaling up of aquaporin water filtration membrane systems are underway. However, there are significant challenges involved in scaling up aquaporin-embedded membrane manufacturing; for example, achieving defect-free membrane fabrication, optimising aquaporin-embedded vesicle deposition and immobilisation in the membrane, and optimising the characteristics of the thin-film formation. For laboratory-scale membrane manufacturing, a 10 cm^2 (10^{-3} m^2) membrane sample can be sufficient for generating initial performance characterisation data. However, industrial production of membranes for large-scale applications can require 1,000 to 100,000 m^2 of membranes, all of which must be prepared with minimal defect densities. For example, less than 1 cm^2 of defects for every 105 cm^2 of membrane surface area is required for gas separations (Park et al. 2017). An initiative underway that could contribute to addressing these challenges was announced in 2023 by Singapore's National Water Agency, which shared its plans to use biomimetic aquaporin membrane modules in a water production facility designed to process 7.7 million litres (1.7 million imperial gallons) per day (Smart Water Magazine 2023).

3.3 Opportunities for use of selective membranes in waste valorisation and metals processing

Membranes are used commonly in the mining, oil and gas industries for separating gas mixtures, treating waste water and removing oil from water (Bolto et al. 2020). For example, reverse osmosis and nanofiltration membrane technologies are currently used in the mining industry for waste water treatment and leachate concentration (Panayotova & Panayotova 2021). Reverse osmosis is commonly used as a post-treatment process for the removal of heavy metals and other toxic compounds from mining-influenced water before water discharge to the environment. Therefore, the infrastructure and expertise needed for deploying new membrane technologies in mining applications does not present a barrier to adoption within industries. However, examples of use of selective membranes for metal and mineral extraction applications remains limited, with the main example case being direct lithium extraction (DLE) from brine where selective membranes can improve DLE efficiency and viability (Fan et al. 2024; Patel et al. 2025). Examples of cation or anion exclusion membranes that can help separate molecules based on ionic charge have been reported, and these are used in electrodialysis processes (Wang & Lin 2024). Also, researchers are working on membrane advances where electrochemical potentials are applied to drive selectivity (Wang et al. 2024b). Use of membranes for selective harvesting of other metals is not widespread beyond research and development activities, and it is more common for development activities to focus on complete metal removal from waste rather than using membranes to harvest metals.

Use of membranes in mineral and metal processing has potential to improve process efficiency and sustainability outcomes by reducing the requirements for chemical reagents and minimising waste (Lair et al. 2024). Current metal and mineral extraction processes, such as liquid-liquid extraction and ion exchange, can be constrained by metal selectivity limitations, and are often resource- and energy-intensive, requiring the use of large quantities of hazardous chemicals and generating toxic wastes (Almohasin et al. 2023). Membranes can reduce pre-treatment and extraction steps by selectively partitioning feedstocks into product and byproduct streams. This selective partitioning could be intensified by the modularisation of selective membranes to enable staged extraction of target metals and minerals (Lair et al. 2024). Selective membranes may also offer more flexibility in terms of being able to process feed solutions of varying chemistries, rather than needing individual feed solution processing optimisation on a case-by-case basis to overcome feedstock composition variability, which many ore-refining practices require. There are commercially available nanofiltration and ion exchange membranes that can distinguish between monovalent and multivalent ions (Tang & Bruening 2020; Kingsbury et al. 2020), and these have mostly been used for the direct processing of brine and removal of problematic contaminants like boron (Zhang et al. 2018; Zhao et al. 2020). However, these types of membranes typically leverage electrostatic interactions between the charge of the membrane surface and the ions in solution, either repelling or attracting ions of the same or opposite charge, respectively, (Epsztein et al. 2020) and offer imperfect selectivity, particularly between ions with the same charge.

The current capability of commercial state-of-the-art reverse osmosis and nanofiltration membranes to selectively separate a single solute from a mixture of solutes is limited (Epsztein et al. 2020). Therefore, the research and development for innovative membranes that allow fit-for-purpose separation functions are needed. Advancements in membrane technology are moving towards membranes capable of molecular recognition, such as BERST, which offer significant advantage in highly selective separation. Molecular recognition is a key feature of biological membranes, and leveraging the functionality of these mechanisms could provide new strategies for difficult-to-extract metals or difficult-to-process waste. For example, REE extraction and processing, in particular, could benefit from bioinspired membrane technologies. Current REE recovery processes by liquid-liquid extraction can include up to 1,500 stages (McNulty et al. 2022).

This complexity is due to the high similarity in chemical properties across REEs and that REE recovery requires significant inputs of solvents, acids and bases, generating large volumes of wastes. Membranes with specificity for individual REEs could support or replace conventional liquid-liquid extraction technologies for REE extraction.

Plants, and some microorganisms, can harness REE properties to enhance their metabolic processes and physiological functions, and have evolved selective membrane transport proteins to facilitate the uptake and transport of REEs (Rocha et al. 2024; McGaughey et al. 2025). These biological structures could be borrowed or their features mimicked to develop selectively permeable membranes suitable for REE extraction and processing. Similar selective transport proteins are described for other critical resources such as nutrients, metals and minerals. Plants require selective transport proteins for all of the molecules that they encounter in the environment, such as aluminium (Al^{3+}), ammonium (NH^{4+}), boric acid ($H_2BO_3^-$), cadmium (Cd^{2+}), calcium (Ca^{2+}), caesium (Cs^+), chloride (Cl^-), chromate (CrO_4^{2-}), cobalt (Co^{2+}), copper (Cu^{2+}), dihydrogen phosphate ($H_2PO_4^-$), hexaaquacobalt(II) ($Co(H_2O)_6^{2+}$), hydrogen (H^+), hydrogen phosphate (HPO_4^{2-}), hydroxide (OH^-), iron (ferrous cation Fe^{2+}, ferric cation Fe^{3+}), lead (Pb^{2+}), lithium (Li^+), magnesium (Mg^{2+}), molybdate (MoO_4^{2-}), nickel (Ni^{2+}), nitrate (NO^{3-}), potassium (K^+), rubidium (Rb^+), sodium (Na^+) sulphate (SO_4^2), zinc (Zn^{2+}) and REEs (De Rosa et al. 2023). Selective permeation membranes will enable targeted and efficient removal of constituents from mining waste to enhance water recovery, reduce residual wastes, and recover resources to generate new revenue streams and offset mine closure costs.

4 Bioderived element resource separation technology

The BERST system is a collection of biomimetic membranes with features inspired by the extraordinary diversity of selective separation functions observed in plants. BERST systems leverage the functions of the nutrient, metal or mineral selective transport proteins that evolved in plants to design structures that enable extraction of permeates of high-purity nutrients, metals or minerals, and clean water from complex feed solutions.

4.1 Function of bioderived element resource separation technology

BERST biomimetic membranes incorporate engineered biological membrane proteins to achieve selective separation. The engineered membrane proteins are derived from the nutrient, metal or mineral selective transport proteins evolved in plants with optimised function for use in synthetic membrane structures. The BERST system is designed as a platform technology that can be adapted for a diverse range of separation applications. This is because the selectivity of the BERST biomimetic membranes depends on which engineered nutrient, metal or mineral selective transport proteins are embedded. Each BERST membrane module can be designed to allow for specific separation of a target nutrient or metal. BERST could then be deployed as a bespoke modular solution for targeted retrieval of multiple high-purity constituents from complex aqueous feedstocks. This means that BERST can be applied in a cascade of membrane processes with common design and operation but different membrane selectivity, enabling sequential recovery of a range of different metals. Use of common engineering and application principles could enable maximum value to be extracted from the often-complex waste resources found in mining-influenced waters.

The structure of BERST systems was inspired by the structure of established hollow fibre biomimetic membrane filters developed for water separation (see Section 3.2), except that the membrane proteins embedded in BERST are selective for target nutrients or metals, rather than only for water molecules. Industrial waste water is pumped into BERST, forcing the waste water to flow through the interior or luminal space of the hollow fibres (Figure 3). The interior surface, or lumen side, of the hollow fibre is coated by a selectively permeable membrane layer. This membrane layer contains vesicles embedded with engineered membrane transport proteins (Figure 3). For the application of extracting target metals from mining wastes, the embedded membrane transport proteins used will be selective for those target metals. The selective membrane proteins enable target solutes to move across the thin-film composite membrane layer and supporting polymer matrix to the permeate side, forming a continuous stream of target solute concentrate. Non-target molecules are unable to pass through the protein-embedded selectively permeable membrane layer, remaining inside the hollow fibres and exiting the BERST module as the outflow. The result is the selective partitioning of feed solution into a product, or permeate, stream where the target metal is concentrated, and a byproduct stream where the target metal is depleted and non-target solution constituents remain. The modularisation of multiple BERST biomimetic membranes, each with distinct metal or mineral molecule selectivity, could enable multiple product permeate streams for further processing, with minimum contamination from unwanted constituents.

BERST biomimetic membrane systems enable flexibility in terms of being able to process feed solutions of varying chemistries using selections of modules, without requiring extensive process optimisation on each case-by-case basis to overcome feedstock composition variability. However, in some cases it may improve efficiency to selectively remove non-target contaminants from industrial waste water prior to selectively separating and concentrating target metals. Additional pre-processing of feed solutions may also be necessary to prolong membrane life span and performance; for example, the removal of fine particulates, or pH adjustment. The reported functional performance parameters of similar protein-embedded membranes for water permeation include a pH range of 2–11 and a temperature range of 10–65°C, beyond which water flux was reversibly reduced (Perry et al. 2015). Depending on the fabrication method, similar biomimetic membranes containing biological components can be stored at room temperature for at least a year without a significant decrease in performance (Zhao et al. 2012; Fuwad et al. 2024). Formulas for calculating system water permeability, solute flux and rejection have been reported (Wagh et al. 2019; Fuwad et al. 2024). For example, solute rejection R (%) = ((1 – (C_p; solute concentration in permeate)/(C_f; solute concentration in feed)) x 100%; and water flux (Jw) = ΔW (increase in weight of draw solution)/Sm (membrane area) and Δt (change in time) are used to assess success in harvesting clean water from waste. However, determining optimal parameters for BERST function and assessing success in harvesting resources from mining waste are likely to require tailoring to the specific application of harvesting metals from wastes.

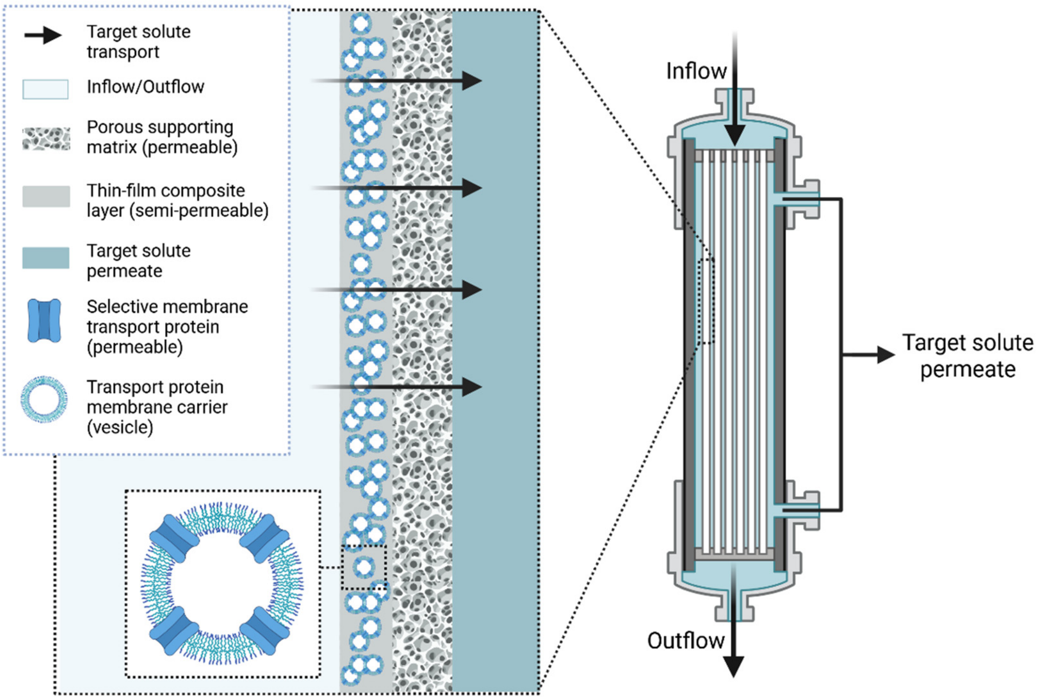

Figure 3 Schematic of a bioderived element resource separation technology (BERST) membrane module. Selective membrane transport proteins are incorporated into vesicles. Vesicles provide a membrane structure to support the function of membrane transport proteins and can be made from a range of different amphiphilic materials such as lipids (as in biological membranes) and polymers. Transport protein-containing vesicles are then integrated into a thin-film composite layer, forming a selective semi-permeable coating supported by a porous typically polymeric matrix

4.2 Early-stage techno-economic assessment considerations

The commercial potential of the BERST biomimetic membrane system for valorisation of mining-influenced water will depend on the ability to produce essential system components at low cost and at the scale required. As an early-stage technology, large uncertainties remain around various component costs and operating parameters, which can make assessing economic viability challenging. However, techno-economic analysis using the best available data to inform cost estimates of components and system configuration can provide indicative cost ranges and help focus research on the areas that can most improve cost competitiveness. Figure 4 shows the contribution of different components to the total cost of purchasing and operating a BERST filter for one year, providing a minimum, middle-point and maximum for the cost estimate range. The analysis used publicly available data for existing biomimetic commercial water filter designs, such as the Aquaporin reverse osmosis unit with protein-embedded membranes (Aquaporin 2023) to inform estimates of capital costs and operating parameters, including flow rates used to assess electricity costs. Using middle-point estimates, the cost of producing the protein contributes 50% to the total cost, followed by the electricity used to run the pump servicing the filter at 28%, then the membrane at 15%. However, electricity use dominates the cost when assuming the minimum estimates for protein production and membrane fabrication, highlighting that these systems have the potential to be produced at low cost.

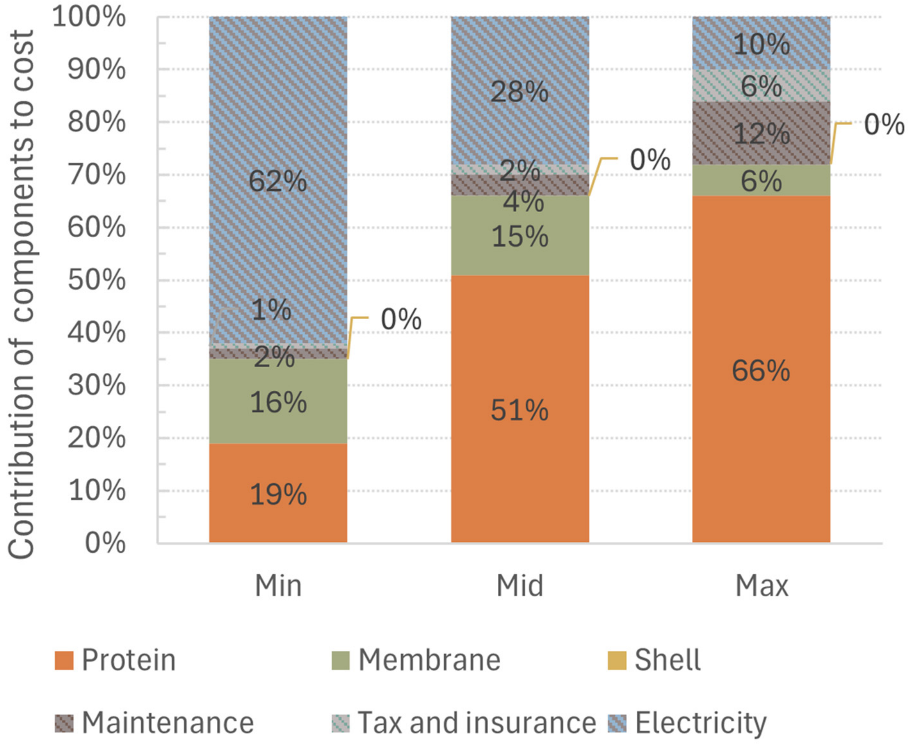

Figure 4 Percentage contribution of different components to the total cost of purchasing and operating a BERST system for one year. Capital costs (filter shell, membrane and proteins) are shown as solid colour bars while operation and maintenance costs (electricity to run the permeate pump, maintenance and tax and insurance) are crosshatched. Data is shown for the minimum (min), middle-point (mid) and maximum (max) of the cost estimate range. Maintenance costs assumed that the system would be 'flushed out' to remove all fouling particulates for 4% of its operational hours, at an estimated cost of 6% of the total capital cost. The percentage values for the components were rounded to avoid decimal points and enable the sum of 100% for each of min, mid and max

Factors that could drive down the costs of manufacturing BERST could be technological advancements in manufacturing membrane technologies, market competition and economies of scale. These are the types of factors that reduced the cost of genome sequencing over time. In 2001 sequencing a genome cost around USD 95 million. The cost dropped to around USD 1 million by 2007, and now it costs around USD 200 to sequence a genome (National Human Genome Research Institute 2021). Protein production constitutes a significant cost contribution to BERST manufacture (Figure 4). This cost is due to the inherent requirements of precision membrane protein expression and purification. Membrane protein production is a cellular phenomenon, meaning cellular energy and machinery are required for their synthesis (Kafri et al. 2016). Some proteins may be well expressed in cell culture systems, for example the AqpZ aquaporin protein used in biomimetic water filter membranes can be expressed in bacteria (*E. coli*) with yields up to 200 $mg.L^{-1}$ of culture (Lian et al. 2009), whereas other membrane proteins may yield 1–10 $mg.L^{-1}$ culture. These protein production parameters will be specific to the type of membrane protein because variation in membrane protein properties influences their efficiency in membrane integration and the ability of the cell culture system to tolerate their overproduction, since changes in membrane permeability can impact cell viability (Scott & Hwa 2011; Tomala & Korona 2013).

Membrane protein purification from culture systems for embedding in synthetic membranes requires disruption of the biological cell membrane and protein stabilisation using speciality non-ionic detergents, which can be expensive (Perry et al. 2015). However, the reduction in the cost of recombinant protein production could be expected to follow a similar trend to that of genome sequencing. Biotechnological innovation has boosted demand for recombinant proteins for various technology applications, leading to rapid market growth. Applications for recombinant proteins include biotherapeutics, enzymes, vaccines, biofuels, polymers and foods (Demain & Vaishnav 2009; Tripathi & Shrivastava 2019). For enzymatic proteins, the market is forecast to grow from USD 6.4 to 8.7 billion at a 6.3% growth rate between 2021–2026 (Barone et al. 2023). The term ‘Moore’s Law’ has been used to describe related trends in the context of semiconductors, where the principle is that the speed and capability of computers can be expected to double every two years as a result of increases in the number of transistors a microchip can contain where the cost of the doubling is minimal. The equivalent of Moore’s Law is likely to apply to the bioeconomy (Shirvani 2024; Wesseler & Zhu 2024). Gains in the economic potential of precision fermentation and protein production processes, which are being driven by new market demands and production innovations (CSIRO 2022), will enable reliable and cost-effective production of the protein components essential for BERST manufacturing at the scale required.

5 Conclusion

Developing and deploying novel separation technologies that can increase the precision of separation and degree of selectivity associated with mining resource extraction is expected to support reducing waste volumes and related closure liabilities (CSIRO 2023). Solute-selective membrane technologies like BERST offer significant opportunities for improving the outcomes of mine closure through mining waste valorisation and treatment. Harvesting critical resources from mining-influenced waters has the potential to change the dynamics of mine closure and support economic rehabilitation. However, further biomimetic membrane research and development is needed to ensure economical technology scale-up and stable performance across varied applications and environments. Recent advancements in precision fermentation and membrane engineering are bringing biomimetic membrane separation technologies closer to realisation and deployment. Accelerating the development and implementation of technologies like BERST is expected to contribute to supporting sustainable mining practices and the creation of circular economies in the future.

Acknowledgement

We thank the Australian National University (ANU) and the Australian Research Council for their support through IM240100006. We thank Rio Tinto for their global Remediation and Valorisation of Mining-Influenced Waters challenge initiative, supporting research and development programs towards leaving a positive legacy for future generations. We thank Christopher Jackson from ANU for support in exploring technoeconomic assessments of membrane separation technologies. We thank team members from our laboratory at ANU for their contribution to the fundamental scientific research underpinning membrane separation biotechnological developments. Thank you Dr Yeorgia Argirou for referencing and editing support.

References

Abid, MB, Wahab, RA, Salam, MA, Moujdin, IA & Gzara, L 2023, 'Desalination technologies, membrane distillation, and electrospinning, an overview', *Heliyon*, vol. 9, no. 2, https://doi.org/10.1016/j.heliyon.2023.e12810

Almohasin, JA, Balag, J, Miral, VG, Moreno, RV, Tongco, LJ & Lopez, ECR 2023, 'Green Solvents for Liquid–Liquid Extraction: Recent Advances and Future Trends', *Engineering Proceedings*, vol. 56, no. 1, https://doi.org/10.3390/ASEC2023-16278

Aquaporin 2023, *Aquaporin Inside CLEAR Classic*, fact sheet, viewed 10 April 2025, https://aquaporin.com/wp-content/uploads/2023/07/CLEAR-Classic-Datasheet_June2023.pdf

Arsic, M, Byrt, C, De Rosa, A, Hilder, P, Iqbal, S, McGaughey, S, ... Xie, Z 2024, 'Biomimetic membrane technology developments relevant to sustainable reuse of resources', *Water e-Journal*, vol. 10, no. 3, https://doi.org/10.21139/wej.2024.007

Bar-On, YM, Phillips, R & Milo, R 2018, 'The biomass distribution on Earth', *Proceedings of the National Academy of Sciences*, vol. 115, no. 25, pp. 6506–6511, https://doi.org/10.1073/pnas.1711842115

Barone, GD, Emmerstorfer-Augustin, A, Biundo, A, Pisano, I, Coccetti, P, Mapelli, V & Camattari, A 2023, 'Industrial production of proteins with *Pichia pastoris- Komagataella phaffii*', *Biomolecules*, vol. 13, no. 3, https://doi.org/10.3390/biom13030441

Bolto, B, Zhang, J, Wu, X & Xie, Z 2020, 'A review on current development of membranes for oil removal from wastewaters', *Membranes*, vol. 10, no. 4, https://doi.org/10.3390/membranes10040065

Byrt, CS, Zhang, RY, Magrath, I, Chan, KX, De Rosa, A & McGaughey, S 2023, 'Exploring aquaporin functions during changes in leaf water potential', *Frontiers in Plant Science*, vol. 14, https://doi.org/10.3389/fpls.2023.1213454

CSIRO 2022, *Proteins of the future: using precision fermentation to develop new ingredients*, viewed 10 April 2025, https://www.csiro.au/en/news/All/Articles/2022/November/proteins-of-the-future-using-precision-fermentation-to-develop-new-ingredients

CSIRO 2023, *Enabling Mine Closure and Transitions: Opportunities for Australian Industry*, prepared for CRC TiME.

Daraz, U, Li, Y, Ahmad, I, Iqbal, R & Ditta, A 2023, 'Remediation technologies for acid mine drainage: recent trends and future perspectives', *Chemosphere*, vol. 311, https://doi.org/10.1016/j.chemosphere.2022.137089

De Rosa, A, McGaughey, S, Magrath, I & Byrt, C 2023, 'Molecular membrane separation: plants inspire new technologies', *New Phytologist*, vol. 238, no. 1, pp. 33–54, https://doi.org/10.1111/nph.18762

Deamer, D 2016, 'Membranes and the origin of life: a century of conjecture', *Journal of Molecular Evolution*, vol. 83, pp. 159–168, https://doi.org/10.1007/s00239-016-9770-8

Demain, AL & Vaishnav, P 2009, 'Production of recombinant proteins by microbes and higher organisms', *Biotechnology Advances*, vol. 27, no. 3, pp. 297–306, https://doi.org/10.1016/j.biotechadv.2009.01.008

Dorey, A & Howorka, S 2024, 'Nanopore DNA sequencing technologies and their applications towards single-molecule proteomics', *Nature Chemistry*, vol. 16, pp. 314–334, https://doi.org/10.1038/s41557-023-01322-x

Drew, D & Boudker, O 2016, 'Shared Molecular Mechanisms of Membrane Transporters', *Annual Review of Biochemistry*, vol. 85, pp. 543–572, https://doi.org/10.1146/annurev-biochem-060815-014520

Epsztein, R, DuChanois, RM, Ritt, CL, Noy, A & Elimelech, M 2020, 'Towards single-species selectivity of membranes with subnanometre pores', *Nature Nanotechnology*, vol. 15, pp. 426–436, https://doi.org/10.1038/s41565-020-0713-6

Fan, F, Ren, Y, Zhang, S, Tang, Z, Wang, J, Han, X, ... Tang, B 2024, 'A bioinspired membrane with ultrahigh Li^+/Na^+ and Li^+/K^+ separations enables direct lithium extraction from brine', *Advanced Science*, vol. 11, no. 35, https://doi.org/10.1002/advs.202402898

Fang, Y, Jiang, J, Hou, X, Guo, J, Li, X, Zhao, D & Xie, X 2022, 'Plant protein-coding gene families: Their origin and evolution', *Frontiers in Plant Science*, vol. 13, https://doi.org/10.3389/fpls.2022.995746

Flagel, LE & Wendel, JF 2009, 'Gene duplication and evolutionary novelty in plants', *New Phytologist*, vol. 183, no. 3, pp. 557–564, https://doi.org/10.1111/j.1469-8137.2009.02923.x

Fuwad, A, Ryu, H, Han, ED, Lee, JH, Malmstadt, N, Kim, YR, ... Jeon, TJ 2024, 'Highly permeable and shelf-stable aquaporin biomimetic membrane based on an anodic aluminum oxide substrate', *npj Clean Water*, vol. 7, https://doi.org/10.1038/s41545-024-00301-0

Habel, J, Hansen, M, Kynde, S, Larsen, N, Midtgaard, SR, Jensen, GV, ... Hélix-Nielsen, C 2015, 'Aquaporin-Based Biomimetic Polymeric Membranes: Approaches and Challenges', *Membranes*, vol. 5, no. 3, pp. 307–351, https://doi.org/10.3390/membranes5030307

Harrington, SA, Connorton, JM, Nyangoma, NIM, McNelly, R, Morgan, YML, Aslam, MF, ... Balk, J 2022, 'A two-gene strategy increases iron and zinc concentrations in wheat flour, improving mineral bioaccessibility', *Plant Physiology*, vol. 191, no. 1, pp. 528–541, https://doi.org/10.1093/plphys/kiac499

He, B, Liu, W, Li, J, Xiong, S, Jia, J, Lin, Q, ... Cui, P 2024, 'Evolution of plant genome size and composition', *Genomics, Proteomics & Bioinformatics*, vol. 22, no. 5, https://doi.org/10.1093/gpbjnl/qzae078

Hélix-Nielsen, C 2018, 'Biomimetic membranes as a technology platform: challenges and opportunities', *Membranes*, vol. 8, no. 3, https://doi.org/10.3390/membranes8030044

Hotaling, S, Kelley, JL & Frandsen, PB 2021, 'Toward a genome sequence for every animal: Where are we now?', *Proceedings of the National Academy of Sciences*, vol. 118, no. 52, https://doi.org/10.1073/pnas.2109019118

Hunter, P 2008, 'A toxic brew we cannot live without', *EMBO reports*, vol. 9, pp. 15–18, https://doi.org/10.1038/sj.embor.7401148

Kafri, M, Metzl-Raz, E, Jona, G & Barkai, N 2016, 'The Cost of Protein Production', *Cell Reports*, vol. 14, pp. 22–31, http://dx.doi.org/10.1016/j.celrep.2015.12.015

Kerr-Phillips, T, Schon, B & Barker, D 2022, 'Polymeric materials and microfabrication techniques for liquid filtration membranes', *Polymers*, vol. 14, no. 19, https://doi.org/10.3390/polym14194059

Kingsbury, RS, Wang, J & Coronell, O 2020, 'Comparison of water and salt transport properties of ion exchange, reverse osmosis, and nanofiltration membranes for desalination and energy applications', *Journal of Membrane Science*, vol. 604, https://doi.org/10.1016/j.memsci.2020.117998

Krämer, U 2010, 'Metal hyperaccumulation in plants', *Annual Review of Plant Biology*, vol. 61, pp. 517–534, https://doi.org/10.1146/annurev-arplant-042809-112156

Kumar, M, Grzelakowski, M, Zilles, J, Clark, M & Meier, W 2007, 'Highly permeable polymeric membranes based on the incorporation of the functional water channel protein Aquaporin Z', *Proceedings of the National Academy of Sciences*, vol. 104, no. 52, https://doi.org/10.1073/pnas.0708762104

Lair, L, Ouimet, JA, Dougher, M, Boudouris, BW, Dowling, AW & Phillip, WA 2024, 'Critical mineral separations: opportunities for membrane materials and processes to advance sustainable economies and secure supplies', *Annual Review of Chemical and Biomolecular Engineering*, vol. 15, pp. 243–266, https://doi.org/10.1146/annurev-chembioeng-100722-114853

Lane, N & Martin, WF 2012, 'The Origin of membrane bioenergetics', *Cell*, vol. 151, no. 7, https://doi.org/10.1016/j.cell.2012.11.050

Li, X, Chou, S, Wang, R, Shi, Lei, Fang, W, Chaitra, G, ... Fane, AG 2015, 'Nature gives the best solution for desalination: Aquaporin-based hollow fiber composite membrane with superior performance', *Journal of Membrane Science*, vol. 494, pp. 68–77, https://doi.org/10.1016/j.memsci.2015.07.040

Lian, J, Ding, S, Cai, J, Zhang, D, Xu, Z & Wang, X 2009, 'Improving aquaporin Z expression in *Escherichia coli* by fusion partners and subsequent condition optimisation', *Applied Microbiology and Biotechnology*, vol. 82, pp. 463–470, https://doi.org/10.1007/s00253-008-1774-x

Lim, YJ, Goh, K & Wang, R 2022, 'The coming of age of water channels for separation membranes: from biological to biomimetic to synthetic', *Chemical Society Reviews*, vol. 11, https://doi.org/10.1039/D1CS01061A

Lindahl, E & Sansom, MSP 2008, 'Membrane proteins: molecular dynamics simulations', *Current Opinion in Structural Biology*, vol. 18, no. 4, pp. 425–431, https://doi.org/10.1016/j.sbi.2008.02.003

Liu, G, Zhou, B, Liu, J & Zhao, H 2021, 'The bionic water channel of ultra-short, high affinity carbon nanotubes with high water permeability and proton selectivity', *Sustainability*, vol. 13, no. 1, https://doi.org/10.3390/su13010102

Lu, C, Bonini, A, Viel, JH & Maglia, G 2025, 'Toward single-molecule protein sequencing using nanopores', *Nature Biotechnology*, vol. 43, pp. 312–322, https://doi.org/10.1038/s41587-025-02587-y

McGaughey, SA, Iqbal, S, De Rosa, A, Caley, JA, Kaksonen, AH, Villa-Gomez, D & Byrt, CS 2025, 'Interactions of rare earth elements with living organisms and emerging biotechnical applications', *Plants, People, Planet*, https://doi.org/10.1002/ppp3.70010

McNulty, T, Hazen, N & Park, S 2022, 'Processing the ores of rare-earth elements', *MRS Bulletin*, vol. 47, pp. 258–266, https://doi.org/10.1557/s43577-022-00288-4

Merchant, SS 2010, 'The elements of plant micronutrients', *Plant Physiology*, vol. 154, no. 2, pp. 512–515, https://doi.org/10.1104/pp.110.161810

Minerals Research Institute of Western Australia (MRIWA) 2024, *Alternative Use of Tailings and Waste*, viewed 19 March 2025, https://www.mriwa.wa.gov.au/minerals-research-advancing-western-australia/focus-areas/alternative-use-of-tailings-and-waste/

Mining Weekly 2024, *Tailings Remining Can Meet Critical Minerals Demand*, viewed 4 April 2025, https://www.miningweekly.com/article/tailings-remining-can-meet-critical-minerals-demand-2024-04-04

National Human Genome Research Institute 2021, *The Cost of Sequencing a Human Genome*, viewed 10 April 2025, https://www.genome.gov/about-genomics/fact-sheets/Sequencing-Human-Genome-cost

Oliva, R, Calamita, G, Thornton, JM & Pellegrini-Calace, M 2010, 'Electrostatics of aquaporin and aquaglyceroporin channels correlates with their transport selectivity', *Proceedings of the National Academy of Sciences*, vol. 107, no. 9, https://doi.org/10.1073/pnas.0910632107

Osman, A, Chen, Z, Elgarahy, A, Farghali, M, Mohamed, IMA, Priya, AK, ... Yap, PS 2024, 'Membrane Technology for Energy Saving: Principles, Techniques, Applications, Challenges, and Prospects', *Advanced Energy & Sustainability Research*, vol. 5, no. 5, https://doi.org/10.1002/aesr.202400011

Panayotova, M & Panayotova, V 2021, 'Application of membrane processes in mining and mineral processing', *Second International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters*, vol. 280, https://doi.org/10.1051/e3sconf/202128008016

Panchy, N, Lehti-Shiu, M & Shiu, SH 2016, 'Evolution of Gene Duplication in Plants', *Plant Physiology*, vol. 171, no. 4, pp. 2294–2316, https://doi.org/10.1104/pp.16.00523

Park, HB, Kamcev, J, Robeson, LM, Elimelech, M & Freeman, BD 2017, 'Maximizing the right stuff: The trade-off between membrane permeability and selectivity', *Science*, vol. 356, no. 6343, https://doi/10.1126/science.aab0530

Patel, SK, Iddya, A, Qian, J & Elimelech, M 2025, 'Approaching infinite selectivity in membrane-based aqueous lithium extraction via solid-state ion transport', *Science Advances*, vol. 11, no. 9, https://doi.org/10.1126/sciadv.adq9823

Pellicer, J, Hidalgo, O, Dodsworth, S & Leitch, IJ 2018, 'Genome size diversity and its impact on the evolution of land plants', *Genes*, vol. 9, no. 2, https://doi.org/10.3390/genes9020088

Perry, M, Madsen, SU, Jørgensen, T, Braekevelt, S, Lauritzen, K & Hélix-Nielsen, C 2015, 'Challenges in Commercializing biomimetic membranes', *Membranes*, vol. 5, no. 4, pp. 685–701, https://doi.org/10.3390/membranes5040685

Quirk, RP, Kinning, DJ & Fetters, LJ 1996, '1 - block copolymers', in G Allen & JC Bevington (eds), *Comprehensive Polymer Science and Supplements*, Pergamon, Oxford, pp. 1–26.

Reeves, RD, Baker, AJM, Jaffré, T, Erksine, PD, Echevarria, G & van der Ent, A 2017, 'A global database for plants that hyperaccumulate metal and metalloid trace elements', *New Phytologist*, vol. 218, no. 2, pp. 407–411, https://doi.org/10.1111/nph.14907

Ren, Q, Chen, K & Paulsen, IT 2006, 'TransportDB: a comprehensive database resource for cytoplasmic membrane transport systems and outer membrane channels', *Nucleic Acids Research*, vol. 28, no. 35, https://doi.org/10.1093/nar/gkl925

Rocha, RA, Alexandrov, K & Scott, C 2024, 'Rare earth elements in biology: From biochemical curiosity to solutions for extractive industries', *Microbial Biotechnology*, vol. 17, no. 6, https://doi.org/10.1111/1751-7915.14503

Sackville, MA, Gillis, JA & Brauner, CJ 2024, 'The origins of gas exchange and ion regulation in fish gills: evidence from structure and function', *Journal of Comparative Physiology B*, vol. 194, pp. 557–568, https://doi.org/10.1007/s00360-024-01545-5

Sands, JM & Layton, HE 2014, 'Advances in understanding the urine-concentrating mechanism', *Annual Review of Physiology*, vol. 76, pp. 387–409, https://doi.org/10.1146/annurev-physiol-021113-170350

Scott, M & Hwa, Terence 2011, 'Bacterial growth laws and their applications', *Current Opinion in Biotechnology*, vol. 22, no. 4, pp. 559–565, https://doi.org/10.1016/j.copbio.2011.04.014

Senovilla, M, Castro-Rodríguez, R, Abreu, I, Escudero, V, Kryvoruchko, I, Udvardi, MK, ... González-Guerrero, M 2018, '*Medicago truncatula* copper transporter 1 (MtCOPT1) delivers copper for symbiotic nitrogen fixation', *New Phytologist*, vol. 218, no. 2, pp. 696–709, https://doi.org/10.1111/nph.14992

Shen, YX, Saboe, PO, Sines, IT, Erbakan, M & Kumar, M 2014, 'Biomimetic membranes: A review', *Journal of Membrane Science*, vol. 454, pp. 359–381, https://doi.org/10.1016/j.memsci.2013.12.019

Shirvani, T 2024, 'The role of bioengineering in building a bioeconomy', *Nature Reviews Bioengineering*, vol. 2, pp. 908–910, https://doi.org/10.1038/s44222-024-00237-7

Smart Water Magazine 2023, *Aquaporin and Singapore's PUB work on biomimetic low-energy RO membrane demonstration*, viewed 10 April 2025, https://smartwatermagazine.com/news/aquaporin/aquaporin-and-singapores-pub-work-biomimetic-low-energy-ro-membrane-demonstration

Sterck, L, Rombauts, S, Vandepoele, K, Rouzé, P & Van de Peer, Y 2007, 'How many genes are there in plants (… and why are they there)?', *Current Opinion in Plant Biology*, vol. 10, no. 2, pp. 199–203, https://doi.org/10.1016/j.pbi.2007.01.004

Sterlitech 2017, *Aquaporin Hollow Fiber FO Membrane Modules (AQPHFFO2)*, viewed 4 April 2025, https://www.sterlitech.com/blog/post/aquaporin-hollow-fiber-fo-membrane-modules-aqphffo2?srsltid=AfmBOor97DHsjFcyJ7AqMPCGhYQnk-D5LAXGeYNVgW0wlzVgjeXMJ0Fa

Sterlitech 2019, *Introducing the Aquaporin Inside HFFO14 Hollow Fiber FO Membrane Module,* viewed 4 April 2025, https://www.sterlitech.com/blog/post/introducing-the-aquaporin-inside-hffo14-hollow-fiber-fo-membrane-module?srsltid=AfmBOoowEf5ZTByhU2NCY7orX6fpAKAkebk6rJb4PolyAAKoFCm-nx_m

Tang, C & Bruening, ML 2020, 'Ion separations with membranes', *Journal of Polymer Science*, vol. 58, no. 20, pp. 2831–2856, https://doi.org/10.1002/pol.20200500

Tomala, K & Korona, R 2013, 'Evaluating the Fitness Cost of Protein Expression in *Saccharomyces cerevisiae*', *Genome, Biology and Evolution*, vol. 14, no. 5, pp. 2051–2060, https://doi.org/10.1093/gbe/evt154

Tripathi, NK & Shrivastava, A 2019, 'Recent Developments in Bioprocessing of Recombinant Proteins: Expression Hosts and Process Development', *Frontiers in Bioengineering and Biotechnology*, vol. 7, https://doi.org/10.3389/fbioe.2019.00420

Tyerman, SD, McGaughey, SA, Qiu, J, Yool, AJ & Byrt, CS 2021, 'Adaptable and Multifunctional Ion-Conducting Aquaporins', *Annual Review of Plant Biology*, vol. 17, no. 72, pp. 703–736, https://doi.org/10.1146/annurev-arplant-081720-013608

Wagh, P, Zhang, X, Blood, R, Kekenes-Huskey, PM, Rajapaksha, P, Wei, Y & Escobar, IC 2019, 'Increasing Salt Rejection of Polybenzimidazole Nanofiltration Membranes via the Addition of Immobilized and Aligned Aquaporins', *Processes*, vol. 7, no. 2, https://doi.org/10.3390/pr7020076

Wang, C, Du, X, Gao, F, Hao, X & Guan, G 2024b, 'Electrochemically switched ion separation technologies: A review on electroactive ion exchange materials and system architectures', *Chemical Engineering Journal*, vol. 490, https://doi.org/10.1016/j.cej.2024.151708

Wang, H, Chen, Z, Feng, L, Chen, Z, Owens, G & Chen, Z 2024a, 'Uptake and transport mechanisms of rare earth hyperaccumulators: A review', vol. 351, https://doi.org/10.1016/j.jenvman.2023.119998

Wang, R & Lin, S 2024, 'Membrane Design Principles for Ion-Selective Electrodialysis: An Analysis for Li/Mg Separation', *Environmental Science & Technology*, vol. 58, no. 7, https://doi.org/10.1021/acs.est.3c08956

Werner, TT, Bach, PM, Yellishetty, M, Amirpoorsaeed, F, Walsh, S, Miller, A, ... Wu, X 2020, 'A geospatial database for effective mine rehabilitation in Australia', *Minerals*, vol. 10, no. 9, https://doi.org/10.3390/min10090745

Wesseler, J & Zhu, M 2024, 'The contribution of the bioeconomy to sustainable development', *Engineering*, vol. 43, no. 12, pp. 25–27, https://doi.org/10.1016/j.eng.2024.08.019

Widmer, J & Norgrove, L 2023, 'Identifying candidates for the phytoremediation of copper in viticultural soils: A systematic review', *Environmental Research*, vol. 216, https://doi.org/10.1016/j.envres.2022.114518

Yuan, M, Liu, C, Liu, WS, Guo, MN, Morel, JL, Huot, H, ... Qiu, RL 2018, 'Accumulation and fractionation of rare earth elements (REEs) in the naturally grown *Phytolacca americana* L. in southern China', *International Journal of Phytoremediation*, vol. 20, no. 5, pp. 415–423, https://doi.org/10.1080/15226514.2017.1365336

Zhang, Y, Almodovar-Arbelo, NE, Weidman, JL, Corti, DS, Boudouris, BW & Phillip, WA 2018, 'Fit-for-purpose block polymer membranes molecularly engineered for water treatment', *npj Clean Water*, vol. 1, https://doi.org/10.1038/s41545-018-0002-1

Zhao, Y, Qiu, C, Li, X, Vararattanavech, A, Shen, W, Torres, J, ... Tang, CY 2012, 'Synthesis of robust and high-performance aquaporin-based biomimetic membranes by interfacial polymerisation-membrane preparation and RO performance characterisation', *Journal of Membrane Science*, vol. 423, pp. 422–428, https://doi.org/10.1016/j.memsci.2012.08.039

Zhao, Y, Wang, H, Li, Y, Wang, M & Xiang, X 2020, 'An integrated membrane process for preparation of lithium hydroxide from high Mg/Li ratio salt lake brine', *Desalination*, vol. 493, https://doi.org/10.1016/j.desal.2020.114620

Zheng, HX, Liu, WS, Sun, D, Zhu, SC, Li, Y, Yang, YL, ... Tang, YT 2023, 'Plasma-membrane-localized transporter NREET1 is responsible for rare earth element uptake in hyperaccumulator Dicranopteris linearis', *Environmental Science & Technology*, vol. 57, no. 17, pp. 6922–6933, https://doi.org/10.1021/acs.est.2c09320