Stage 1 Report Project 3.15

Algae-based technologies for improved environmental outcomes and sustainable post-mining futures

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List of abbreviations

ACARP	Australian Coal Industry's Research Program
ACCU	Australian Carbon Credit Unit
AD	Anaerobic digestion
ADE	Anthropogenic Dark Earths
AMD	Acid mine drainage
AMPS	2-acrylamide-2-methyl propane sulfonic acid
ANZECC	Australian and New Zealand Environment and Conservation Council
APVMA	Australian Pesticides and Veterinary Medicines Authority
ARD	Acid rock drainage
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ATS	Algal turf scrubber
AU$	Australian dollar
BCR	Bubble column reactor
BOD	Biochemical oxygen demand
CAGR	Compound annual growth rate
CapEx	Capital expenditure
CCU	Carbon capture and utilisation
CER	Clean Energy Regulator
CN	Cetane number
COD	Chemical oxygen demand
CO_2-e	CO_2 equivalent
CPI	Consumer Price Index
CRC	Cooperative Research Centre
CRC TiME	Cooperative Research Centre for Transformations in Mining Economies
CSIRO	Commonwealth Scientific and Industrial Research Organisation
3D	Three dimensional
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DIC	Dissolved inorganic carbon
DMTA	Dynamic mechanical thermal analysis
DNA	Deoxyribonucleic acid

DOM	Dissolved organic matter
€	Euro
EA	Environment Authority
e.g.	*Exempli gratia* (for example)
EOWC	End of Waste Code
EPA	Environment Protection Authority
ERA	Environmentally relevant activities
ERF	Emissions Reduction Fund
ESG	Environmental, social, and governance
FAME	Fatty acid methyl esters
FANS	Filamentous Algae Nutrient Scrubbers
FSANZ	Food Standards Australia New Zealand
GARD	Global Acid Rock Drainage
GMO	Genetically modified organism
HPH	High-pressure homogenisation
HRT	Hydraulic retention time
ICARD	International Conference on Acid Rock Drainage
ICER	Industrial and Commercial Emissions Reduction
ICMM	International Council on Mining & Metals
i.e.	*Id est* (that is)
INAP	The International Network for Acid Prevention
IP	Intellectual Property
LCA	Life cycle assessment
MCA	Minerals Council Australia
MODS	Microalgae oil-based dust suppressant
MU	Murdoch University
N/A	Not available
NOx	Nitric oxide (NO) and nitrogen dioxide (NO_2)
NSCME	Nutrient-supplemented coal mine effluent
NSW	New South Wales
OpEx	Operating expenditure
OPR	Open raceway pond
PBR	Photobioreactor

PEF	Pulsed electric field
PFAS	Per- and polyfluoroalkyl substances
γ-PGA	γ-Polyglutamic acid
PHA	Polyhydroxybutyrate
PIMR	Pipe Insert Microalgae Reactor
PM_{10}	Particulate matter with diameter of ≤ 10 µm
PMLU	Post mining land use
PNRS	Periphyton nutrient removal systems
PPE	Personal Protection Equipment
PRBC	Photorotating biological contactor
PRC	Progressive Rehabilitation and Closure
PRCP	Progressive Rehabilitation and Closure Plan
PRI	Principles for Responsible Investment
REE	Rare earth elements
RES	Regional Economic Solutions Pty Ltd
ROI	Return on investment
RSM	Response surface methodology
SDBS	Sodium dodecyl benzene sulfonate
SHMS	Safety and Health Management System
SMC	Safeguard Mechanism Credits
SMF	Safeguard Mechanism Facility
TEA	Techno-economic analysis
TEK	Traditional ecological knowledge
TELCA	Integrated techno-economic and life cycle analysis
UNEP	United Nations Environment Programme
UQ	The University of Queensland
US$	United Stated dollar
USA	United States of America
US EPA	United States Environmental Protection Agency
VOC	Volatile organic compound
WHO	World Health Organisation
w/w	Weight/weight

Executive Summary

Background and aim

Mining has been and continues to be an important driver for Australia's economic prosperity and sustainable development, but it has also created risks to people and the environment that may persist long after mining operations cease. Environmental challenges at mine sites include physical disturbance of land and air emissions, the generation of mining and metallurgical wastes, and mine water. Moreover, the loss of valuable land and water assets can impact the long-term sustainability of local communities.

This collaborative study between the Commonwealth Scientific and Industrial Research Organisation (CSIRO), The University of Queensland (UQ), and Murdoch University (MU) explored the potential of algal technologies for improved environmental outcomes and sustainable post-mining futures. It was supported by the Cooperative Research Centre for Transformations in Mining Economies (CRC TiME) via the Australian Government Department of Industry, Science and Resources through the Cooperative Research Centres Program. Additional support was provided by South 32, Fortescue, Rio Tinto, Heidelberg Materials, Mineral Research Institute of Western Australia, CSIRO, the University of Queensland, Murdoch University, Queensland Mine Rehabilitation Commissioner, and Energy Australia. This report is based on a literature review and stakeholder engagement through surveys, interviews and a workshop conducted as part of Stage 1 of the project with CSIRO ethics approval (Ethics Clearance 230/23).

Mine water pH can vary from acidic to alkaline, with differences in the concentrations of sulfate, metals, and metalloids across different types of mines. Various micro- and macroalgae have been detected and identified in mine waters, indicating that their cultivation at mine sites should be possible if suitable growth conditions are provided. Algal growth requires sunlight, carbon dioxide, and essential macro- and micronutrients. In certain scenarios, pre-treatment of mine water may be required to adjust pH, remove some toxic elements, sulfate or other salts, suspended solids, and/or to add nutrients to support algal growth.

Potential benefits of algal technologies

Integrating algae into mining scenarios offers significant benefits by combining ecological restoration with economic value generation. Algae cultivation can treat mine water and sequester carbon dioxide, and algal biomass supports mine waste stabilisation and dust suppression and improves plant growth when used as a fertiliser and biostimulant. Moreover, algal biomass can be used as a raw material for the production of bioplastics, biofuels, pigments and animal feeds (Figure 1). Algal cultivation may also be complementary to other water uses such as aquaculture which may use algae as a feedstock and in turn provide nutrients for algal cultivation. The application of algae at mine sites accelerates ecological recovery while reducing environmental impacts, such as pollutant levels and greenhouse gas emissions. Additionally, algae-based technologies create sustainable business opportunities, turning post-mining land into economically productive ecosystems (Figure 2). This dual approach not only enhances rehabilitation outcomes but also ensures long-term sustainability for mining sites through the development of business opportunities for ongoing value generation beyond mine closure. Moreover, algal cultivation at mine sites may create jobs and offer opportunities to engage Traditional Owners and other local communities.

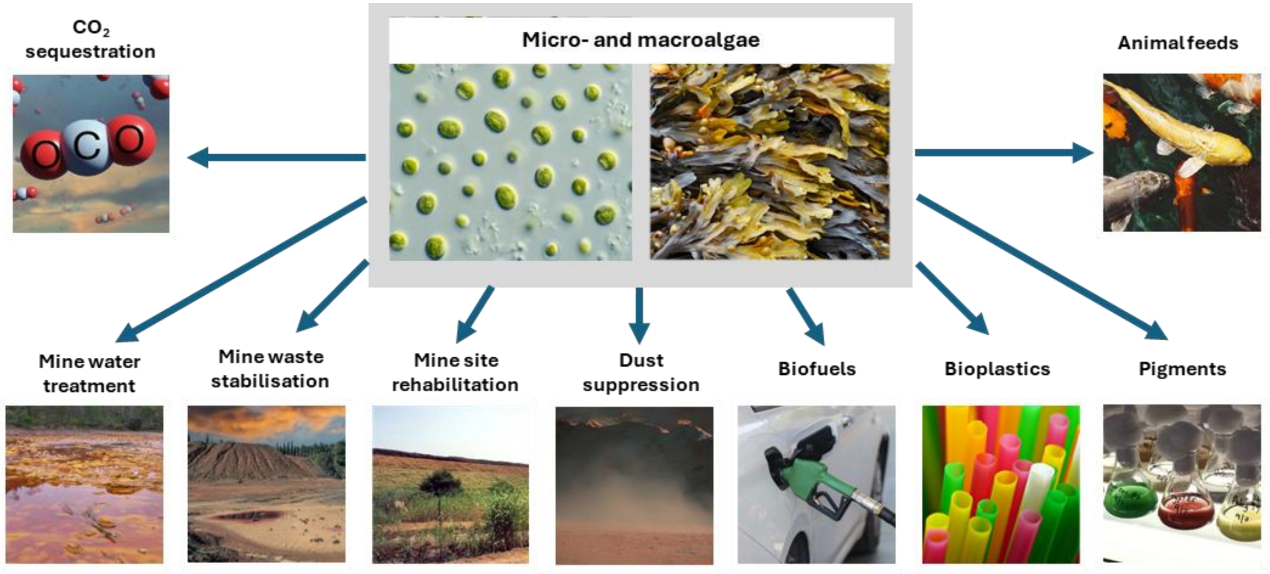


Figure 1: Examples of algal technologies for improved environmental outcomes and sustainable post-mining futures.

Selection of algal species and cultivation, harvesting and processing technologies

The selection of suitable algal species and cultivation systems for implementation in mine sites can include 1) reviewing mine site characteristics and aim for algal processes, 2) the selection of algal species based on their growth rate and suitability to the mine site conditions and application, 3) identifying possible mine water treatment or amendment needs, 4) the selection of algal cultivation systems, 5) the selection of algal harvesting and processing systems, 6) the verification of algal end products in terms of yield, quality and suitability of biomass residue for other applications, and 7) the optimisation of the process. The growth rate of algae is a key factor influencing the time required for scaling up algal cultivation. Large-scale microalgal cultivation can be carried out in open raceway ponds, closed photobioreactors, floating photobioreactors or biofilm-based algal turf scrubbers. Macro-algal cultivation systems can utilise free-floating algae, or biomass adhered to the bottom of the water body or solid substratum, e.g., using rope or raft systems. Most commonly used microalgal harvesting methods include centrifugation, filtration and flocculation. Macroalgal harvesting can be conducted either manually with cutting tools or through mechanical harvesting using amphibious vehicles, boats, land-based long-armed vehicles equipped with suction apparatus, rotating mowers, cutters, rotating blades and dredgers. Whole algae biomass can be used as is for several applications (e.g., feeds, supplements, fertilisers), however in some scenarios cell disruption is required for the extraction of valuable components (e.g., oils, proteins, pigments). This can be carried out through mechanical, chemical, enzymatic, thermal, electrical or other emerging technologies.

Regulatory and other constraints for the application of algal technologies

Regulatory requirements that need to be considered if planning algal cultivation and use at mine sites include 1) land use agreements (e.g., Indigenous land use agreements and mining lease commercial conditions), 2) environmental permits and compliance (e.g., water use license, waste management and rehabilitation requirements, 3) health and safety standards for occupational, algal process and product safety, and 4) biodiversity and ecosystem protection (e.g., non-invasive species and ecosystem monitoring). Mine rehabilitation guidelines provide a framework for the systematic recovery of ecosystems, including the stabilisation of mine waste, restoration of vegetation, and improvement of water quality. The assembly of a regulation database, consisting of government, industry and societal regulations that impact algae biomass production, processing and products specifically at mine sites could support industry to identify regulatory barriers and opportunities.

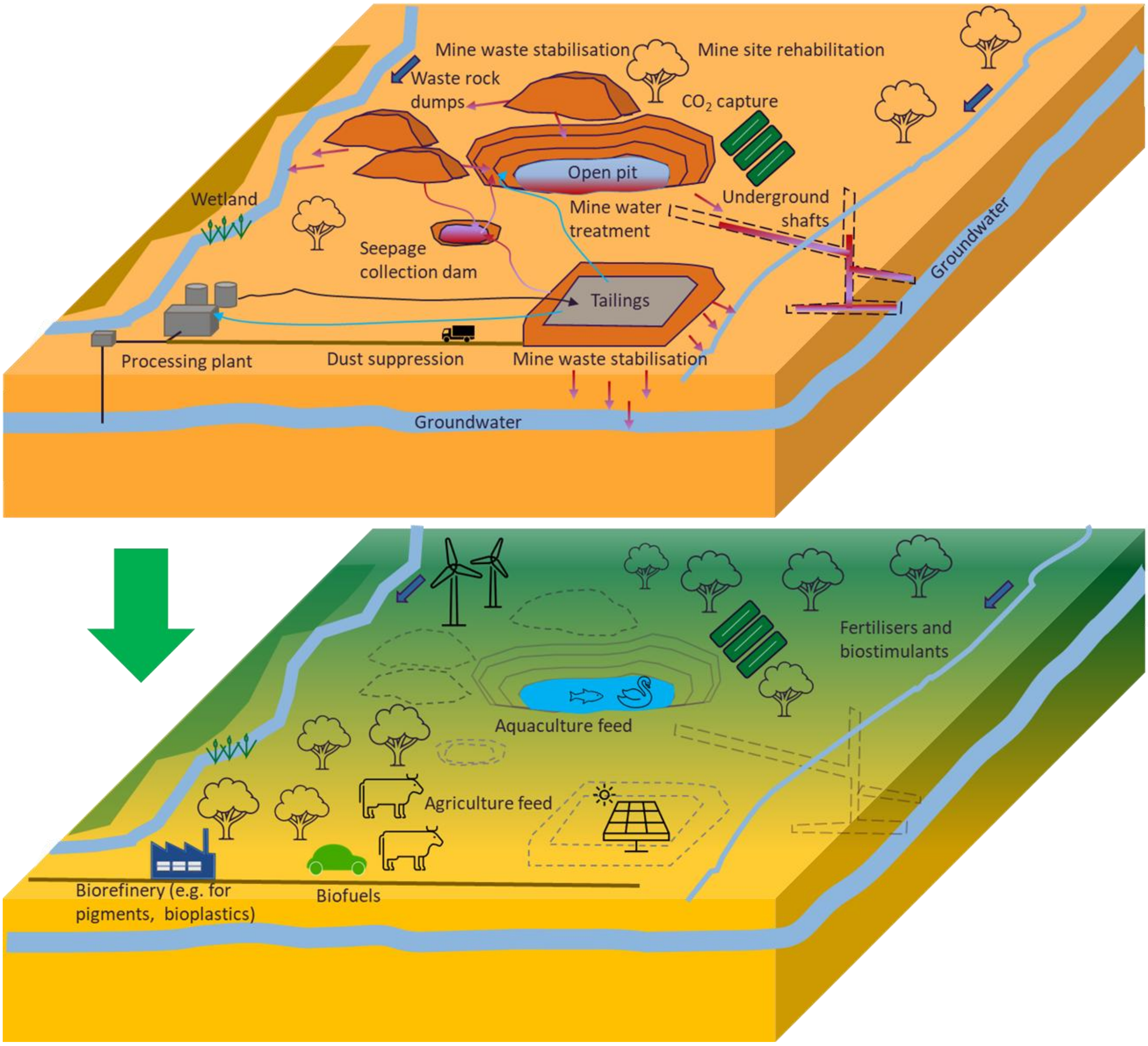


Figure 2: Embedding algal biotechnology in mining operations for improved environmental outcomes and sustainable post-mining futures.

Business case for the application of algal technologies at mine sites

The application of algal technologies at mine sites offers significant economic, social, and environmental benefits, all of which can be quantified through various metrics. Estimates of algal production cost vary with various growth systems and geographic locations, typically being in the order of 10-100 AU$ kg^{-1} of dry algal biomass. The global algae markets are rapidly increasing with a value of US$1.9-5.3 billion in 2023 and estimated annual growth of approximately 5-6%. The market size and value of algal products vary widely depending on the application. For bulk algae products to become cost competitive, multi-product biorefineries will allow compensation of current production costs to achieve profitability. Additionally, algae production costs can be reduced through technical refinement, policy optimisation and scale. Algal cultivation can enable industrial ecology and symbiotic relationships with nearby industries, where CO_2

emissions and nutrient rich wastewater streams from these industries can support algal growth while the algae purify the exhaust gases and wastewater.

A business case for the establishment of algae production within the context of Australian mining sites will consist of many economic, environmental and social aspects, which are heavily dependent on location, site, algae strain, cultivation technology and end-product(s). The implementation of the algae within a mining context will involve various phases, starting with site selection and definition of the site-specific objective, which will inform the selection of the most feasible technologies that could be implemented, followed by due diligence to determine economic, social and environmental opportunities as well as risks. To ensure the successful commercialisation of algae-based products from mining contexts, a comprehensive path to market is required, incorporating market research and analysis, product development and testing, commercial partnerships, regulatory compliance, and marketing efforts. Key considerations for a solid business case for algal technologies include: 1) defining project scope and objectives, 2) site and resource availability, 3) technologies, 4) market analysis, 5) financial projections, 6) regulatory and compliance considerations, 7) risks and mitigation strategies, 8) social and community impacts, 9) sustainability and environmental impacts, 10) strategic partnerships and collaboration, 11) pathways to market, and 12) long-term vision and scalability.

Knowledge gaps and opportunities for potential Stage 2 project scope

Several knowledge gaps for further research on mine site algal technologies were identified: 1) strain selection and cultivation optimisation for mine water conditions, 2) product development for various applications, 3) process development, 4) environmental impact assessment, 5) cost, revenue and economic viability assessment, and 6) increasing the understanding on regulatory frameworks. Based on the research gaps, opportunities for the potential Stage 2 project scope include the characterisation of mine water samples, metagenomic analysis of algae at mine sites, the isolation of algal strains from mine water, and the high throughput growth optimisation of algal strains. Moreover, the use of algal biomass for direct or indirect mine water treatment, mine waste stabilisation, dust suppression and mine site rehabilitation can be explored. Further study could also include a bioeconomic survey and product option analysis, process design and techno-economic analysis, nutrient waste stream inventory, life cycle assessment of selected algal technologies, development of a database on regulatory constraints, engagement with First Nations communities and identification of opportunities for possible pilot-scale test work. Further stakeholder engagement is required to identify the most promising targets for a possible Stage 2 project scope.

1. Introduction

Mining has been and continues to be an important driver for Australia's economic development, and metal ores, minerals and coal products contribute over half of the country's export revenue (Werner et al., 2020). However, with the increasing demand for mineral resources, the negative impacts of mining are also growing (Zhang et al., 2023a). Mining creates risks to people and the environment with the potential to persist long after mine sites are closed. Mining can also result in the destruction of Australia's natural and First Nations heritage, cause decline in biodiversity and adversely impact ecosystem services that provide social, ecological and economic benefits to people at landscape to regional scales and beyond (Cresswell et al., 2021). With net-zero emissions goals on the horizon, the production of energy transition elements is increasing at unprecedented rates, as is the mass of mine waste and polluted water. At the same time, nearly 240 Australian mines are predicted to close by 2040, with expenditure on mine closure and rehabilitation activities expected to exceed $4-8 billion annually (Banfield et al., 2023).

Physical disturbance

Mining activities disturb vast land areas with above and underground mining, roads and other infrastructure. Depending on the size of mine, the areas can span over thousands of hectares (Personal communication, 2024). Above ground mining requires the removal of vegetation and topsoil for mine workings such as open pits and the associated waste rock disposal areas, as well as ore processing facilities (Hudson et al., 1999). Although topsoil is often collected separately for use during mine site rehabilitation, topsoil deficit remains a challenge at many mine sites. Habitat loss and degradation cause changes in species distributions, loss of biodiversity, and disruption of food chains (Cresswell et al., 2021; Zhang et al., 2023a). Ecosystem services, such as erosion control, water and air purification, carbon sequestration, and oxygen release are also impacted (Zhang et al., 2023a).

Energy consumption and air emissions

Approximately 5-7% of all energy generated globally from fossil and nuclear fuels as well as renewable sources has been estimated to be used for mining practices, such as drilling, blasting, excavating, hauling rock to surface, crushing and grinding (Johnson, 2015). As a result of the high energy consumption, mining operations also cause notable greenhouse gas emissions and thus contribute to climate change. Land-based mining is also among the major Australian heavy industries with the largest air emissions (Australian Government Department of Agriculture, Water and the Environment, 2020) of carbon monoxide, sulfur dioxide, coarse particulate matter (PM_{10}), volatile organic compounds (VOCs) (Cresswell et al., 2021), and NOx emissions (Personal communication, 2024). Dust sources in mining operations are drilling, blasting, mineral handling and transportation by vehicles, crushing, screening, grinding, conveying, construction activities and wind erosion. Dust can be a notable health hazard for miners (Liu and Liu, 2020).

Mining and metallurgical wastes

In open pit mining the amount of waste rock is commonly 2-3 times the amount of ore produced. Therefore, large volumes of waste rock are removed from pits and deposited in nearby areas. Waste rock may contain various metals, but the grades are considered to be subeconomic for utilisation. If not properly managed, waste rock may be eroded resulting in the generation of metal-containing water and sediments (Hudson et al., 1999). In addition to waste rock piles, ore residues in heap leach piles also contain residual metals and other contaminants that can become a source of contamination (Hudson et al., 1999).

The concentration of metals through beneficiation processes such as milling and flotation create tailings waste, that contains undesired minerals. The tailings slurries are pumped into large impoundments for disposal (Hudson et al., 1999). The cumulative mine tailings generated globally was estimated to be 282.5 billion tons or 217.3 km^3 in 2021, and the annual growth rate of tailings was estimated to be 12.3 km^3

based on the Global Tailings Review by the International Council on Mining & Metals (ICMM), United Nations Environment Programme (UNEP) and Principles for Responsible Investment (PRI) (LePan 2021).

Mine water

Mining activities can have various impacts on water availability and quality. The quality of mine water depends on the types of minerals mined. Mine drainage can be acidic (pH <6), neutral (pH 6-9) or alkaline (pH >9) (Plante et al., 2021), and in terms of salinity can be classified as freshwater (salinity <1,000 mg L^{-1}), brackish water (salinity 1,000-10,000 mg L^{-1}), saline (salinity 10,000-35,000 mg L^{-1}) or brine (salinity >35,000 mg L^{-1}) (Nordstrom et al., 2015). Mine drainage and mineral processing effluents can also have elevated concentrations of various metals, metalloids, sulfate and other oxyanions, and in some cases radionuclides (Gräfe et al., 2010; Tan et al., 2016; Lakaniemi et al., 2019; Yan et al., 2022; Daraz et al., 2023). The environmental impacts of mine drainage are severe and widespread in many countries (Jarvis and Younger, 2000). Chemical changes caused by mine water in receiving water bodies include changes in pH and salinity, destruction of bicarbonate buffering, deoxygenation and increase in soluble and particulate metal concentrations. Physical changes include increased turbidity, decreased light penetration, sedimentation and sorption of metals. Toxic elements can cause acute or chronic toxicity, or changes in the behaviour, respiration, osmoregulation, acid/base balance, reproduction or migration of organisms as well as death of sensitive species. Ecological impacts include habitat modification, niche loss, reduction in primary productivity, bioaccumulation in food chain, loss of food source or prey and food chain modification. Additionally, mine drainage can cause socioeconomic impacts such as flooding, subsidence, corrosion, decrease of drinking, agricultural, aquacultural, industrial or recreational water quality, aesthetic loss and human health impacts (Gray, 1997; Jarvis and Younger, 2000; Beck et al., 2020).

Social and economic impacts

Much of Australia's mining occurs on land that is subject to land rights and Native Title. For example, in the Northern Territory, over 80% of the extracted mineral value comes from land owned by First Nations people (Northern Land Council, 2021). Nationwide, over 60% of active mines are near Indigenous communities (Minerals Council of Australia, 2021). Mining has an impact on First Nations People caring for Country and can damage Indigenous heritage (Australian Government, 2016; Cresswell et al., 2021). The loss of valuable land and water assets can notably impact the long-term sustainability of local communities.

Legacy mines

Australia has a legacy of over 50,000 orphaned and abandoned mines that cause ongoing risks to the environment as well as human health and safety (Unger et al., 2012; Campbell et al., 2017, Werner et al., 2020). Inactive mine landscapes can be severely affected by waste disposal, air, soil and water pollution, and socioeconomic and cultural impacts. These impacts are not only limited to immediate mine sites but can also extend to the surrounding environments and communities (Werner et al., 2020). The cumulative impacts of past and present mining activities are substantial and poorly understood, with severe legacy issues remaining to be addressed (Roche and Judd, 2016). The rehabilitation costs of mine sites may vary from hundreds of thousands to many millions of dollars. For example, the total liabilities in Queensland alone were estimated to be approximately $13.7 Billion in 2023-2024 financial year (Office of the Queensland Mine Rehabilitation Commissioner, 2024).

Algal technologies as a potential solution

Various physical-chemical and biological approaches have been developed to reduce the environmental footprint of mining. Algae-based technologies offer various opportunities to mitigate the environmental impacts of mining during operations and after closure. Through photosynthesis, algae sequester CO_2 into biomass, allowing possible offsetting of carbon emissions. Algae can also generate alkalinity and facilitate the removal of contaminants from mine water. Moreover, algal biomass can be used for dust suppression, the stabilisation of reactive mine wastes and mine site rehabilitation. The cultivation of algae at mine sites may also provide opportunities for the manufacture of valuable products such as pigments, bioplastics, biofuels and animal feed. This presents the potential to establish a bio-based economy, creating job opportunities for local communities. This CRC TiME project explores the potential to reduce the environmental footprint of mine sites through algae-based CO_2 sequestration, mine drainage prevention and treatment, dust suppression and mine site rehabilitation, and support sustainable post-mining futures and innovative bio-based supply chains for business solutions. The project has included a literature review, as well as engagement with stakeholders through surveys and interviews (see Appendix A for engaged stakeholders) conducted with CSIRO ethics approval (Ethics Clearance 230/23). The report covers a review of micro- and macroalgae that could be cultivated at mine sites, technologies for algal cultivation, harvesting and beneficial use at mine sites and algal products that could create bio-based supply chains to identify research gaps. Opportunities and constraints for cultivating and using algae at mine sites are also discussed and a strategy for engaging with First Nations communities developed. A business case is presented with estimates of the costs involved in setting up algal systems and market opportunities and economic potential for revenue generation. Finally, research gaps are identified and a number of areas for future research are outlined for possible Stage 2 of the project.

2. Knowledge and technology review

2.1 Examples of mine water chemistries

Typical metal and sulfate concentrations in acidic, neutral, alkaline and saline mine drainage as a function of pH are shown in Figure 3 (A and B, respectively) and examples of mine water chemistries are shown in Figure 4: Acid mine drainage (AMD) compositions from various parts of the world: A) Major anions, B) major cations, C) major metals, D) minor and trace metals and metalloids (Data from Naidu et al, 2019).

Acid mine drainage (AMD) or acid rock drainage (ARD) is generated when reduced minerals are exposed to water and oxygen resulting in their oxidation (Banks et al., 1997; Christensen et al., 1996). The oxidation of the minerals can occur for example, in waste rock piles, tailings, pit walls and underground workings and seams (Kaksonen and Puhakka, 2007; Qureshi et al., 2016; Wright et al., 2018). The most common family of reduced minerals are the sulfides (Banks et al., 1997), which are stable under dry anoxic conditions, such as undisturbed ore deposits (Robb, 1994). The oxidation of pyrite (FeS_2) and other minerals with the generic formula of MS_2 leads to the production of protons (Banks et al., 1997), dissolution of metals and release of sulfate (Abinandan et al., 2018). Ferric iron acts as an oxidant for sulfide mineral oxidation, with iron-oxidising microorganisms acting as a catalyst for the oxidation of ferrous iron to ferric iron (Edraki et al., 2005). The oxidation of other metal sulfides also releases metals and sulfate. However, the oxidation of sulfides with the generic formula of MS do not release acid. The acidity generated by metal sulfide oxidation results in notable decrease in the pH of water only when it exceeds the alkalinity available as bicarbonate in water, or the alkalinity in mineral phases (Banks et al., 1997). Acidic conditions also result in further dissolution of metals from metal oxides and carbonates (van Houten and Lettinga, 1995). AMD is often characterised by pH of approximately 2-6 (Abinandan et al., 2018), although in extreme cases the pH can even be negative (Nordstrom et al., 2000; Plante et al., 2021), and sulfate is the dominant anion (Nordstrom et al., 2015). AMD can contain sulfate and various metals at concentrations up to hundreds or thousands of milligrams per litre (Daraz et al., 2023). Depending on the mineralogy, mine drainage may also contain selenate (Tan et al., 2016) or uranium (Lakaniemi et al., 2019). Moreover, nitrate may be present in mine waters as a result of the use of explosives (Yan et al., 2022).

For mine waters with pH values of 6-9, most trace metals are insoluble and strongly sorbed (Nordstrom et al., 2015). On the other hand, anionic metals and metalloids, such as arsenate, arsenite, chromate and molybdate, are more soluble at circumneutral to basic pH because of their negative charge. At high pH, metals become more soluble because of their amphoteric nature (Nordstrom et al., 2015). Very few examples of alkaline mine drainage have been reported in the literature (Nordstrom et al., 2015), and the conditions and processes that lead to the formation of alkaline mine drainage are not well understood (Plante et al., 2021). However, an example of alkaline wastewater generating mineral processing is the Bayer process which converts bauxite to alumina. The Bayer process waste streams include various organic contaminants with oxalate as a major impurity (Cheng et al., 2023) and red mud. Red mud has a pH of approximately 11-13, contains silicon, iron, aluminium, and titanium along with sodium, calcium and traces of rare earth metals (Gräfe et al., 2010; Gräfe et al., 2011; Archambo and Kawatra, 2020). Potentially harmful elements may also be present including vanadium, chromium, gallium, arsenic, thorium and uranium some of which may emit ionising radiation above typical background rates (Gräfe et al., 2010). Under certain conditions, alkaline mine drainage can also occur unrelated to bauxite processing, for instance at abandoned placer gold mines (Craw et al., 2023).

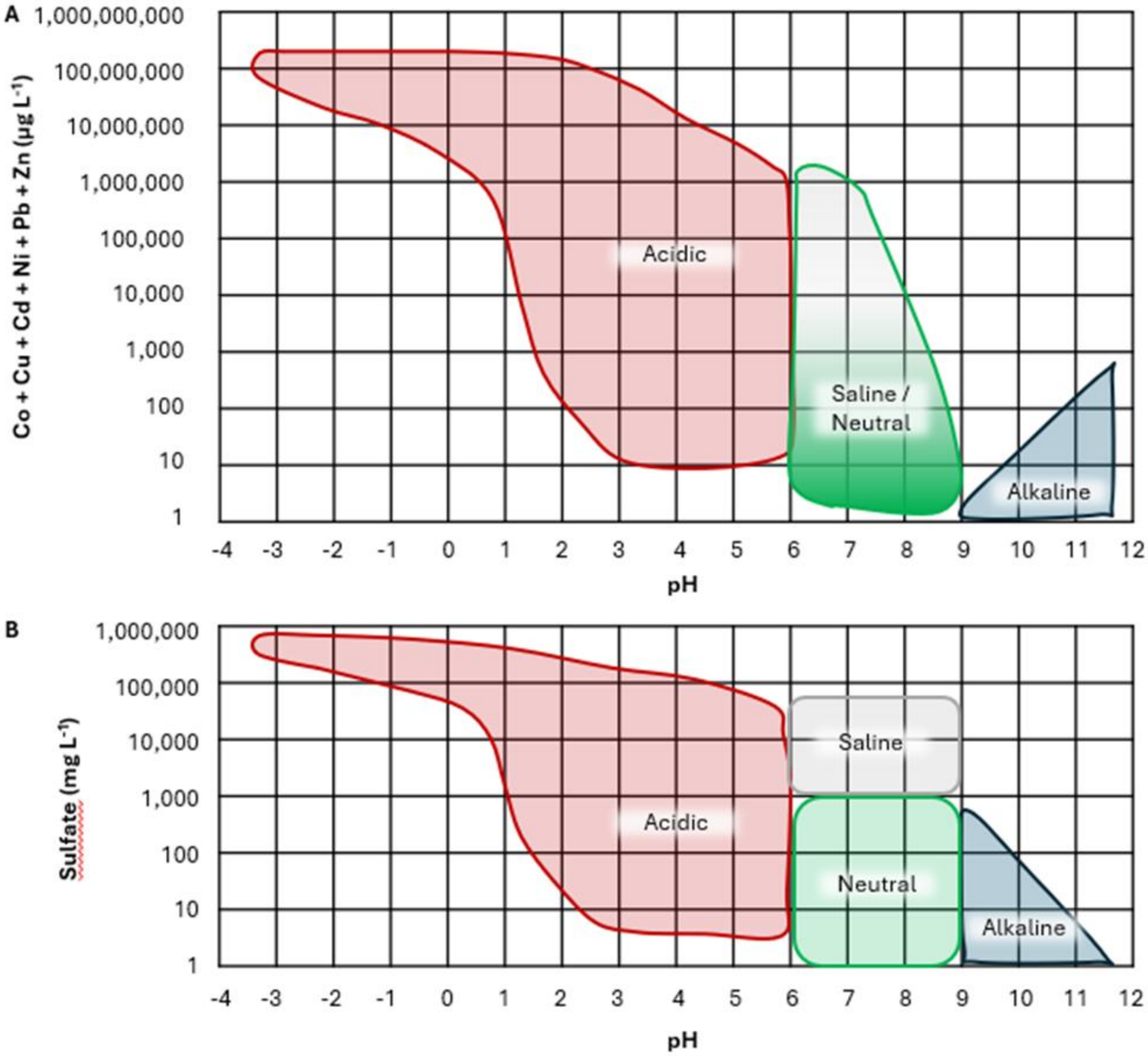


Figure 3: Typical A) metal and B) sulfate concentrations in acidic, neutral, alkaline and saline mine drainage as a function of pH (Adapted from Plumlee, 1999; The INAP, 2009; Nordstrom et al., 2015; Plante et al., 2021).

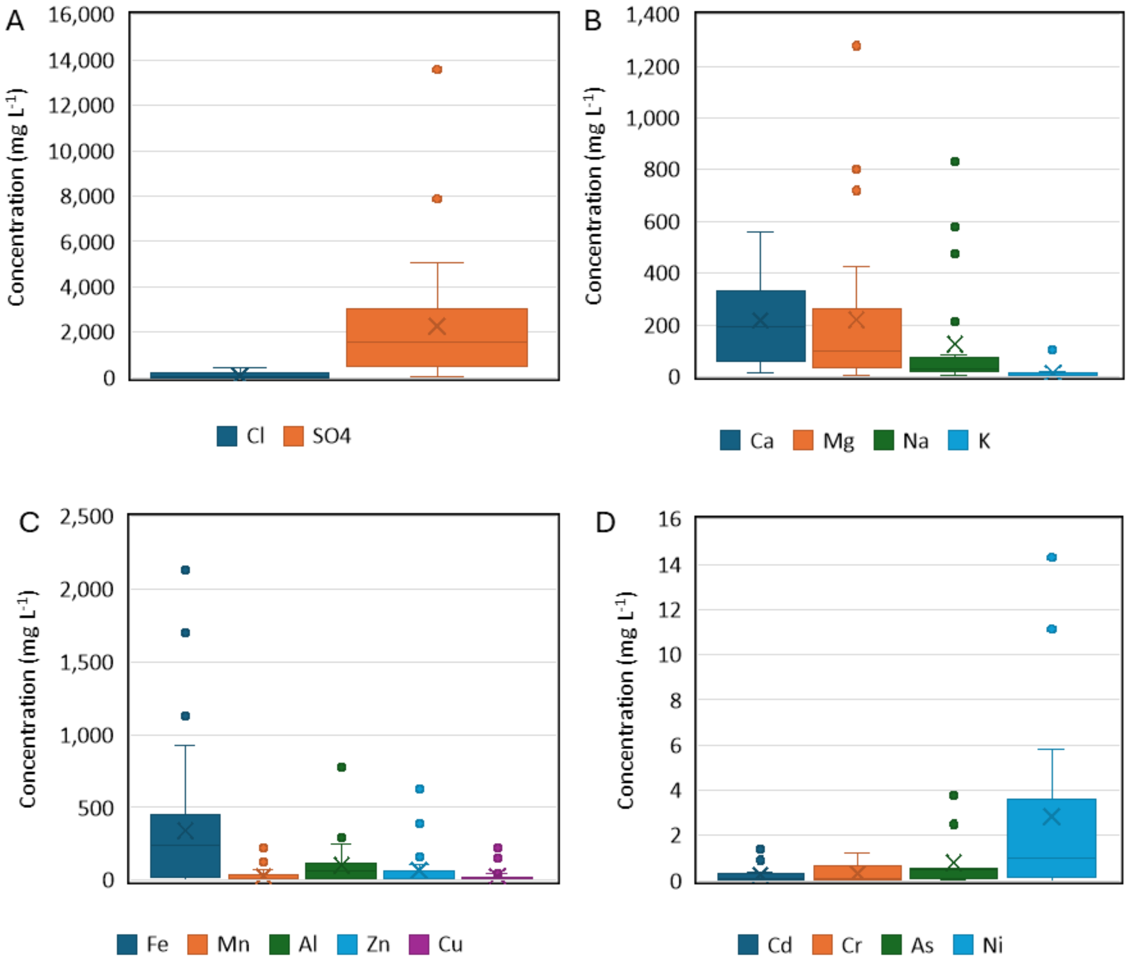


Figure 4: Acid mine drainage (AMD) compositions from various parts of the world: A) Major anions, B) major cations, C) major metals, D) minor and trace metals and metalloids (Data from Naidu et al, 2019).

2.2 Potential for cultivating algae at mine sites

2.2.1 Algae and their growth requirements

Algae comprise a collective of “apparently primitive, plant-like organisms which contain chlorophyll *a*, have oxygenic photosynthesis (usually) and are not specialised land plants” (Borowitzka, 2016). There are currently approximately 50,000 species of algae described (Guiry, 2024). Based on their size, algae can be classified as either microalgae or macroalgae. By definition, microalgae are microscopic and tend to have single cell, filamentous or clumping morphology. This is in contrast to macroscopic macroalgae such as seaweeds and freshwater multicellular species. Algae vary in their tolerance to extremes of temperature, pH, light and nutrient concentrations in their growth media.

The primary building blocks of their biomass include the essential elements carbon (C), nitrogen (N) and phosphorous (P). These are generally incorporated in fixed proportions at approximately C:N:P of 106:16:1, - a feature of algae biology referred to as the ‘Redfield ratio’ (Redfield, 1934; Ketchum and Redfield, 1949). As this ratio refers to the stoichiometry of elements, the actual mass ratio is approximately 41:7:1 of C:N:P. Additional micronutrients which may be required include sodium (Na), chlorine (Cl), magnesium (Mg), calcium (Ca), potassium (K), sulfur (S), and iron (Fe), along with trace elements selenium (Se), copper (Cu), manganese (Mn), zinc (Zn), cobalt (Co), molybdenum (Mo), boron (B) and silicon (Si) (Chu, 1942; Sunda et al., 2005). These may be taken up and utilised in deterministic proportions under ideal growth conditions, however there is considerable natural variation depending on the species (Garcia et al., 2018; Finkel et al., 2016; Sardans et al., 2021).

Under extreme conditions the proportions of elements utilised can have more variability (Ketchum and Redfield, 1949). For example 'luxury' uptake of phosphorous when phosphate is plentiful (Solovchenko et al., 2019), improved protein production dependent on available nitrogen source (Fatini et al., 2021) and amplified carbon uptake due to nitrogen deprivation or increased salinity (Zhu et al., 2015; BenMoussa-Dahmen et al., 2016). Moreover, extracellular polymers exuded by algae and interactions with other microbes in their aquatic surroundings also offer important sites of chemical exchange exterior to the algal cell (Bhaskar and Bhosle, 2005; Ayre et al., 2021; Banerjee et al., 2021).

2.2.2 Algae that could be cultivated in mine water

Various micro- and macroalgae have been detected and/or used at mine sites or grown in mine water. The following sections discuss some examples of algae that could be cultivated at mine sites.

Microalgae

A multitude of microalgae have been detected at various mine sites across the globe, covering over 40 different genera (See Figure 5 and Figure 6). Many of these microalgae may provide robust options for further study of algal cultivation directed toward mine site applications. The microalgae discussed in the following sections have been selected to target particular types of mining wastewaters for which they might be suitable, however further study is needed to verify the productivity of these in large scale cultivation trials.

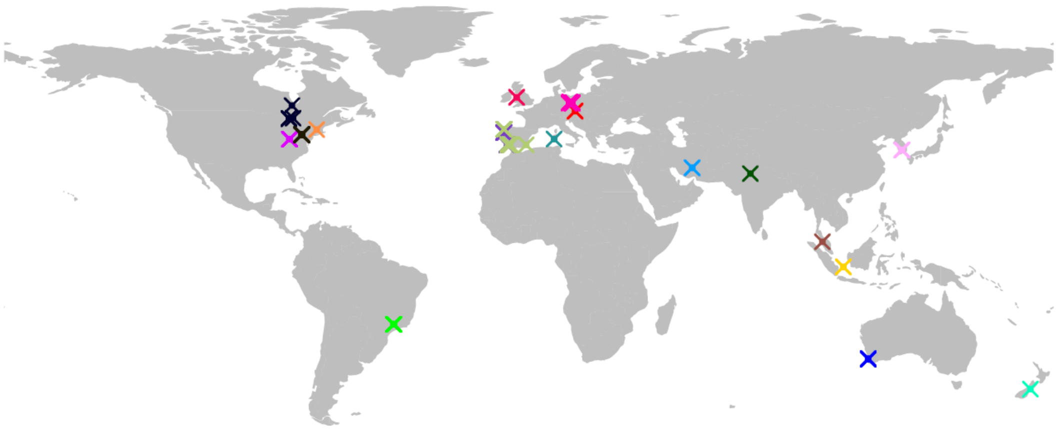


Figure 5: Mine site locations across the globe where microalgae have been detected.

Locations on this map correspond with those on Figure 6. Some adjacent locations have been grouped into the same colour and label (Data from Amaral-Zettler, 2012; Dean et al., 2019; Eibl et al., 2014; Flor et al., 2022; Fuentes et al., 2016; Fyson et al., 2006; Gauthier et al., 2022; Gomes et al., 2021; Gonzalez-Toril et al., 2014; Kumar et al., 2016; Lessmann et al., 2000; López-Archilla et al., 2001; Lucheta et al., 2013; Moser and Weisse, 2011; Nancucheo and Johnson, 2012; Novis, 2019; Orandi et al., 2007; Orandi and Lewis, 2013; Prasanna et al., 2011; Senhorinho et al., 2019; Sheoran and Bhandari, 2005; Soru et al., 2019; Steinberg et al., 1998; Stevens et al., 2001; Susanti et al., 2021; Tan et al., 2020; Valente and Gomes, 2007; Verb and Vis, 2000; Yun et al., 2014).

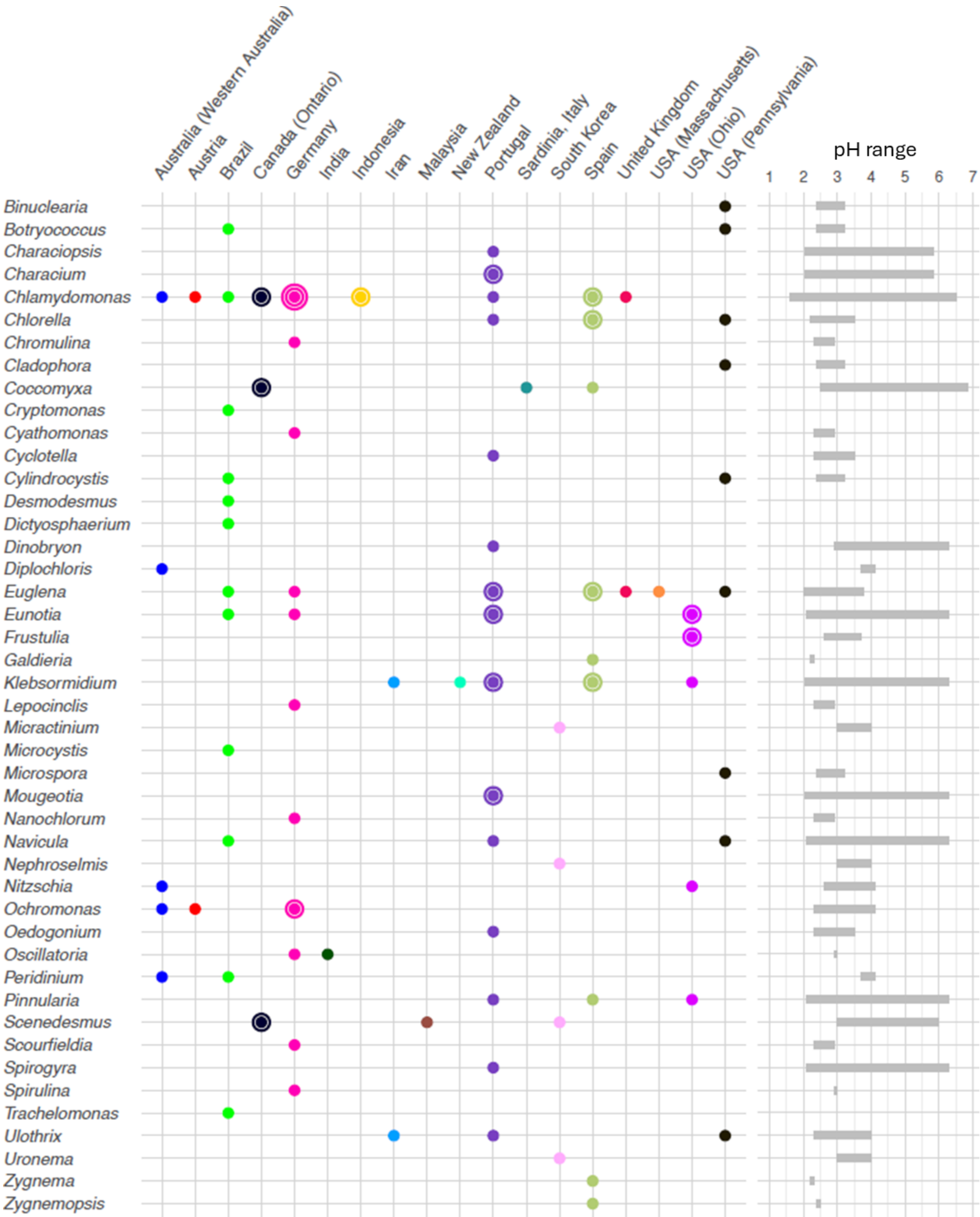


Figure 6: Microalgal genera detected at mine sites in various countries.

Each additional detection (across multiple reports) corresponding to a particular genus and location is represented by an additional coloured circle around the dot on the chart. The pH range shown indicates the minimum and maximum pH readings taken from water sources where these algae were detected. References for this data are shown in the caption of Figure 5.

Microalgae for treating acidic mine drainage (AMD)

One approach to finding microalgal species that could be cultivated in acid mine water (AMD) is to bioprospect for species already acclimated to AMD conditions. The demanding process involving exposure to extreme conditions, cell-growth and reproduction over many generations can apply a strong selection pressure favouring acclimation to extreme growth conditions. Given sufficient time-frames, divergence in genetics and morphology may lead to the emergence of distinct algal species from a common ancestor, with unique traits to tolerate conditions characteristic of AMD. For example, Novis (2019) grew acidophilic *Klebsormidium* sp. under AMD conditions in New Zealand and the strain featured traits divergent from other *Klebsormidium* strains such that it could be classified as a new algae species. A study by Costas et al. (2007) detected randomly occurring genetic variation which can offer adaptative advantages to extreme conditions and tended to take place in some species such as *Dictyosphaerium chlorelloides*, regardless of environmental exposure. However, ongoing selection pressure may encourage these beneficial adaptative phenotypes to become dominant. This seems to indicate that for the appropriate species, either in the field or at the laboratory these phenotypic and genetic characteristics can be shaped over sufficient timeframes to further accommodate tolerance to extreme conditions of interest. Abinandan et al. (2020) reported that over 100 generations of cell division, AMD-acclimated *Desmodesmus* sp. and *Heterochlorella* sp. exhibited differences in cell size, higher lipid production and lower protein production when compared with non-AMD growth media, although the stability of long-term culture may have been impeded. Naturally occurring algal cultures which have been exposed to AMD may offer superior genetic stock to further optimise toward wastewater remediation purposes.

The microalgae species identified here cover a variety of algae classifications, from the red algae *Galdieria sulphurarin* to diatoms such as *Pinnularia subcapitata* and the flagellated euglenid *Euglena mutabilis*. The green algae genus *Chlamydomonas* appeared in fourteen different samples across four different continents and stands out due to its wide-ranging habitat and resounding success at being able to survive extremely acidic environments. Within this genus also resides the model organism *Chlamydomonas reinhardtii*, with its fully mapped genome which may expedite further genetic studies of related algae species. Algae with the appearance of cyanobacteria - often more familiar with alkaline conditions - such as *Oscillatoria* sp. and *Arthospira* (formerly *Spirulina*) sp. also have appeared in some reports, although evidence for long-term growth of species in these genera under these AMD conditions needs to be confirmed (Steinberg et al., 1998).

The bioprospecting samples from dozens of AMD sites across the globe reiterate the diversity of algal species which have demonstrated their resilience to growth under conditions of high acidity and extreme sulfur concentrations. Studies to date have only begun to assess some of the growth performance and remediation potential of these species, and further pilot trials and long-term growth experiments must be done to amend this gap in current knowledge.

Rather than taking the bioprospecting approach, algae with already established commercial markets such as *Chlorella* sp., *Spirulina* sp. and *Haematococcus* sp., notable for their value as sources of health-promoting antioxidants, biofuel and wastewater remediation potential (Skjånes et al., 2013; Silva et al., 2020; Ayre and Moheimani, 2024) may be acclimated and tested to enhance bioremediation potential and improve resistance to pathogens and undesirable contamination. For example, a trial of *Haematococcus pluvialis* grown under acidic conditions (pH 4) when compared to a more neutral pH range (pH 5-9) demonstrated improved resistance to the lethal fungal pathogen *Paraphysoderma sedebokerensis* leading to improved overall production of the valuable antioxidant pigment astaxanthin (Hwang et al., 2019). Abinandan et al. (2019) tested the acclimation of *Desmodesmus* sp. and *Heterochlorella* sp. in a growth experiment at pH 3 over the course of several weeks and found that although growth was inhibited due to the lower pH, there were indications of reasonable phenotypic plasticity and acclimation already apparent within this short duration. Further study of acclimation using robust species such as *Chlorella* sp., renowned for their resilience and growth under high ammonia conditions (Ayre et al., 2017) may still offer unrealised potential, as isolation of *Chlorella protothecoides* var. *acidicola* in AMD by Nancucheo and Johnson (2012) hints that other strains in this genus may be capable of acclimation to acidic growth conditions.

Furthermore, many algal culture collections already contain acidophilic species with promise for application to AMD remediation. For instance, Hirooka and Miyagishima (2016) obtained *Galdieria sulphuraria* strain 074 which had been originally sourced from Indonesia over four decades ago (Gross and Schnarrenberger, 1995) and compared its growth to a more recently isolated *Pseudochlorella* sp. under laboratory conditions using very acidic water from Japanese hot springs. In this study, the supplementation of nitrogen was required along with a small adjustment from pH ≈1.5 to 2, however the growth obtained was similar between completely synthetic and spring-water based media, with chlorophyll, lipid, and phycocyanin production all indicative of healthy growth rates. This study highlights some of the potential growth performance of these acidophilic strains, however, although phosphorus was plentiful in the spring water, nitrogen was deficient reiterating the need for minimum nutrient requirements to be met. *Galdieria sulphuraria* has a strong track record of numerous studies investigating its acidophilic characteristics, along with indications to tolerate high temperature growth conditions (Sydney et al., 2019). Along with *Galdieria sulphuraria*, Abiusi et al. (2022) trialled growth of algal species *Stichococcus* (*S.*) *bacillaris*, *Viridiella* (*V.*) *fridericiana*, *Chlamydomonas* (*C.*) *pitschmannii* and *Chlamydomonas acidophila* and performed some investigations into mixotrophic growth, high temperature tolerance and varying light conditions. Growth at pH 2 did not occur in some species, however, *C. pitschmannii* and *S. bacillaris* were able to grow when the pH was adjusted to 2.9±0.2 while *V. fridericiana* and *C. acidophila* successfully grew at pH 2.1±0.2. Higher temperatures and higher light intensity were inhibitive under some of the conditions tested. These studies demonstrate the variety of growth conditions which may have a bearing on productivity, such as pH, temperature and nutrient availability (Abiusi et al., 2022).

One prominent challenge facing studies of algal remediation of AMD is that laboratories are rarely situated close to mine sites where AMD samples can be obtained easily. The logistical hurdles associated with transporting fresh AMD samples to comply with a particular experimental regime make studies using fresh actual AMD samples difficult to find in the literature. There are exceptions to this such as reported in the study by Olem and Unz (1980) working at the Experimental Mine Drainage Treatment Facility, Pennsylvania, USA (associated with the U.S. Environmental Protection Agency) and Abinandan et al. (2020) based in Newcastle, New South Wales (NSW), Australia, studying algal growth, both using AMD samples obtained from locally sourced coal mining operations. Kumar et al. (2016) also studied algal growth using AMD samples from an AMD-impacted acid lake pit (again coal mine related) in Western Australia and was able to transport samples and commence experiment from source to laboratory mesocosm within 24 hours of collection. However other studies have looked toward the development of synthetic AMD formulations to work around this concern. For instance, Orandi and Lewis (2012) produced a synthetic AMD water to match the average nutrient profile of AMD samples obtained from Sar Cheshmeh copper mine in Iran. The recipe included 22 chemical ingredients including anions (Cl^-, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, CO_3^{2-}), cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and heavy metals (Cu^{2+}, Mn^{2+}, Zn^{2+}, Ni^{2+}, Co^{2+}, Fe^{2+}, Cr^{3+}, Sb^{3+}, Al^{3+}, Ag^+, Pb^{2+} and Se^{2+}). Several heavy metals found in the Sar Cheshmeh AMD samples (Cd, Bi and As) were excluded due to extreme toxicity. This 'Synth-AMD' recipe was used for experiments looking at biofilm culture uptake of heavy metals (Orandi and Lewis, 2013). Olaueson and Stokes (1989) also formulated a 'modified' variant of an earlier synthetic AMD based medium made by Cassin (1974) referred to as 'Acid Medium' formulated to match conditions in acid bog wetland environments. These growth media have been used for studies on *Euglena mutabilis* and *Chlamydomonas* sp., however as discussed earlier, each AMD or acidic waterbody is likely to feature unique site-specific characteristics.

Microalgae for alkaline mine and process water

The relatively recent history of alumina refining, and tightly controlled containment of alkaline wastewater from alumina refineries have limited the opportunities for algae to acclimate and colonise refinery waste areas. Reports of microalgae samples isolated directly from red mud waste itself could not be found, although bacteria have been isolated from bauxite waste in India (Mathiyazhagan, 2011; Narayanan et al., 2020). Nevertheless, there are naturally occurring environments with very high alkalinity which may have allowed microalgae to adapt to conditions analogous to those present in the waste streams from alumina refineries. Some examples of these include deep-sea vents along the fracturing edges of diverging tectonic plates, or geothermal hotspots with unusual extremes of heat and alkalinity. Additionally, hyperalkaline lakes formed by repeated cycles of rainfall and evaporation may be another environment with extreme concentrations of carbonate and related minerals (Craw et al., 2023).

A study by Amaral-Zettler (2012) exploring abandoned mine sites as well as alkaline hydrothermal vents, found most organisms growing under alkaline conditions tended to be non-algal organisms such as annelids, gastrotrichs, amphipods, rotifers and insects. However, genetic analysis has shown the presence of diatoms belonging to the class Fragillariophyceae which could be located across both high and low pH conditions. Genetic material in alkaline conditions could not be resolved to the species level but to several genus level designations: *Diatoma*, *Staurosira*, *Tabellaria* or *Asterionella*. Other studies have similarly found diatoms to be one of the more prominent alkaline tolerant microalgae species (Reavie and Smol, 2001), which may be in part due to sheer numbers of different species and high degree of diversity of these organisms, with over 16,000 living diatom species currently described (Guiry, 2024).

Microbial mats also tend to feature prominently in alkaline hot springs with cyanobacteria and photosynthetic green bacteria often occurring together in these samples (Tank et al., 2017; Bennett et al., 2022; van der Meer et al., 2010). Although the photoautotrophic bacteria such as Chloroflexi do not fall within the same grouping as algae (due to different photosynthetic pigments compared with plants and algae), these microbes may still play an important role alongside useful alkaliphilic cyanobacteria. Some of the cyanobacteria species such as *Synechococcus* spp. and *Leptolyngbya* sp. (Tank et al., 2017) can fix nitrogen (Steunou et al., 2006; van der Meer et al., 2010) and therefore may improve the macronutrient ratios available in these aquatic ecosystems if greater algal biomass productivity is desired. The cyanobacterium *Thermosynechococcus* sp. was also present in these hot spring environments (Tank et al., 2017) but does not fix nitrogen (Rasul et al., 2024).

Picoplanktonic algae species have been detected in hypersaline and hyperalkaline conditions, such as *Picocystis* sp. (Roesler et al., 2002) in a 160 km^2 hypersaline lake in California, USA. This aquatic environment features a pH of 9.8, stratification and high concentrations of sulfur, ammonia and methane. Other *Picocystis* sp. have been observed in similar high alkalinity and hypersaline conditions under both low and high temperature extremes in samples from Asia, Africa and Russia as well as oceanic environments (Pálmai et al., 2020).

One of the distinct advantages of cultivating these alkaliphilic algal species is that there is less competition by other contaminants (Touloupakis et al., 2016). Some commercially valuable species such as *Arthrospira platensis* (formerly *Spirulina*) have been cultivated to take advantage of this feature. Other laboratory grown organisms from culture collections have also demonstrated suitability for growth in highly alkaline conditions. An example is the cyanobacterium *Synechocystis* sp. strain PCC 6803, a model organism with a completely sequenced genome, is salt-tolerant and can tolerate pH 10 (Summerfield and Sherman, 2008). A preliminary study using a 0.1% concentration of red mud to grow *Desmodesmus quadricauda* found intracellular accumulation of lanthanide elements, hinting toward future optimisation toward bioremediation of red mud if grown at very dilute concentrations (Cizkova et al., 2019). Dubey and Dubey (2011) grew *Oscillatoria* sp., *Lyngbya* sp., and *Phormidium* sp. cyanobacteria with up to 4% red mud concentrations with some success.

Due to the extremely high pH, growing microalgae on undiluted red mud may be very challenging if not impossible under current technical constraints, however there may be reason to support ongoing study of algal growth on this challenging waste product. Dilution strategies involving seawater or fresh-water under conditions of plentiful rainfall may offer some freedom to explore microalgae treatment, or perhaps recovery of recalcitrant metals such as Fe, Al and Ti, or rare earth metals such as cerium (Ce), yttrium (Y) and lanthanum (La) (Cizkova et al., 2019; Náhlík et al., 2021). Other opportunities for technical advancement may involve combining red mud waste as a neutralising agent to improve the pH of AMD or utilise carbonates which may be generated from the reaction of CO_2 with red mud (Mucsi et al., 2021) and subsequently provide inorganic carbon to improve algal mediated carbon sequestration.

Macroalgae

Various macroalgae have also been used at or near mine sites as bioindicators or for remediation purposes. Table 1 shows some examples of these. Marine macroalgae/seaweed have been well documented to bioaccumulate metals efficiently. One of the most common uses is the treatment of acid mine drainage (AMD). A recent study used three brown seaweed species to quantify the impact of acid mine drainage (AMD) from an abandoned copper mine site in Wales, U.K. These species were *Fucus serratus, Fucus vesiculosus and Ascophyllum nodosum.* The three species acted as effective bioindicator species, enabling high resolution mapping of pollutant dispersal. The *Fucus* species, sampled next to the AMD outflow at this mine indicated high metal bioaccumulation (>250 mg Fe g^{-1}, >6 mg Cu g^{-1}, >2 mg Zn g^{-1}, >190 µg As g^{-1}) and evidence of algal toxicity indicating severe pollution at the site (Chalkley et al., 2019).

Other effective macroalgae bioremediators include *Sargassum polycystum*, which was tested for metal content near an abandoned lateritic nickel mine on Manicani Island in the Philippines. *Sargassum polycystum* accumulated high levels of Pb, Cu, and Ni, with significantly higher levels of Ni, in the mining runoff stream, this study indicating the integral bioremediation role this seaweed has in rehabilitating the seawater post mining (Corales-Ultra et al., 2019). Another robust green seaweed species *Ulva lactuca* efficiently removed between 60-90% of a group of rare earth elements in seawater (Y, La, Ce, Pr, Nd, Eu, Gd, Tb, Dy) when tested against seven other seaweeds, providing alternative ore extraction systems, as well as providing remediation of seawater (Pinto et al.,2020). Work in Chile investigated the impact of mine waste on two seaweed species, *Scytosiphon lomentaria* and *Ulva rigida*, using oxidative stress biomarkers and heavy metal determination in water and seaweed tissues. They found that Fe and As were the highest accumulating metals within the seaweeds, and both strains had higher antioxidant activity (Gaete Olivares et al., 2016). A second study in Chile used the seaweed *Lessonia nigrescens* to remediate Cu and Cd but was found to be more effective at Cu (Andrade et al., 2006). Oberholster et al. (2018) reported *Microspora tumidula* to bioaccumulate S and P at a pH of 5 in South African wetland (Oberholster et al., 2018). A US study on 26 streams in Ohio surveyed algal biodiversity over four site visits and noted both species of microalgae and macroalgae, with the two most promising species being microalgae *Klebsormidium rivulare* and *Microspora tumidula* for AMD containing Fe and Al (Verb and Vis, 2001).

Table 1: Macroalgal species used as bioindicators or for remediation purposes. AMD = acid mine drainage; REE = rare earth element.

Macroalgal species	Metals and metalloids removal or indication of impact	Locations	References
Marine species			
Fucus serratus *Fucus vesiculosus* *Ascophyllum nodosum*	As, Cd, Cu, Fe, Pb, Zn removed	Wales, U.K. (AMD)	Chalkley et al., 2019
Scytosiphon lomentaria *Ulva rigida*	Fe, Cu, Zn, Cd, Cr, As, Mo removed	Chile (Mine waste)	Gaete Olivares et al., 2016
Sargassum polycystum	Pb, Cu, Ni removed	Manicani Island, Philippines (AMD)	Corales-Ultra et al., 2019
Ulva lactuca *Ulva intestinalis* *Fucus spiralis* *Fucus vesiculosus* *Osmundea pinnatifida* *Gracilaria* sp.	REEs (Y, La, Ce, Pr, Nd, Eu, Gd, Tb, Dy) removed from seawater	Rare earth elements in Seawater (REEs)	Pinto et al., 2020
Lessonia nigrescens	Cu, Cd removed	Chile (AMD)	Andrade et al., 2006
Freshwater species			
Oedogonium sp. (3 strains)	Cu, Mn, Ni, Cd, Zn, As, Mo, Se bioaccumulation	Australia (Industrial waste)	Ellison et al., 2014
Oedogonium crissum	Mg, Ca, S, P bioaccumulation	South Africa (Wetlands)	Oberholster et al., 2018

The use of **freshwater macroalgal species** for metal accumulation has also been tested on industrial waste liquids, using strains from the macroalgal genus *Oedogonium*. Three species from this genus were isolated from different locations in Australia and were found to grow on industrial metal contaminated waste samples, enabling rapid bioconcentration of metals (Cu, Mn, Ni, Cd and Zn) more rapidly than metalloids (As, Mo and Se). These macroalgal strains from the genus *Oedogonium* have demonstrated the potential to be used in scaled bioremediation programs across a range of geographic regions (Ellison et al., 2014). Other species of *Oedogonium* have also been found to have bioaccumulation characteristics, *Oedogonium crissum,* showed the highest bioaccumulation of Ca and Mg at a pH of 7, when treating sulfur in AMD water in South Africa (Oberholster et al., 2018).

2.2.3 Selection process for algal species and systems

A number of factors can influence the selection of algal species and systems. Figure 7 shows a framework of seven steps oriented towards the development of an algae selection process, which can be followed through in sequence.

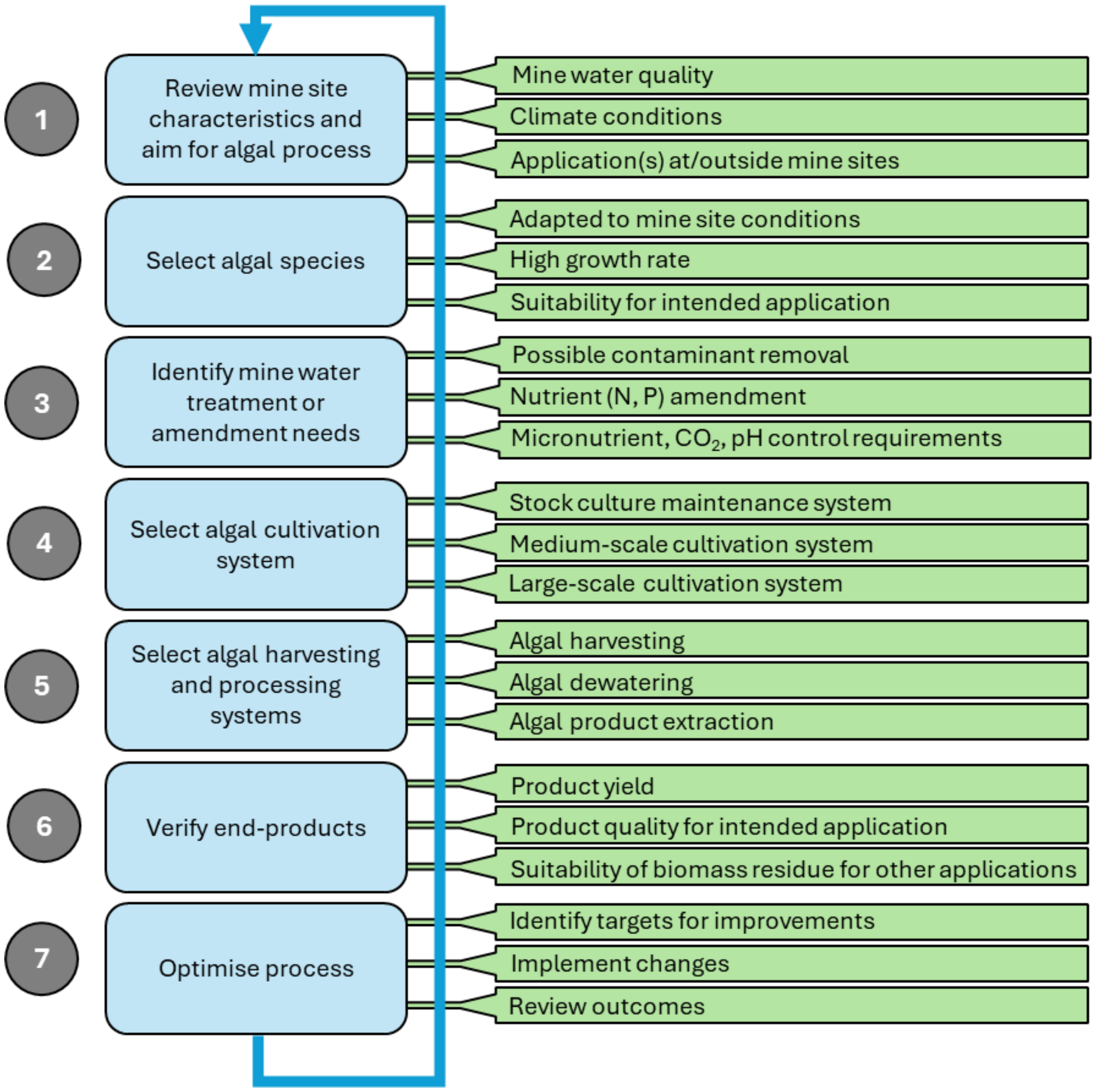


Figure 7: Process flow chart to enable the selection and optimisation of algal species and systems.

Step 1: Reviewing mine site characteristics and the aim of the algal process

The selection of algal species and systems for mine sites first requires the reviewing of mine site characteristics, such as mine water quality and climate conditions, and the identification of the intended application for the algae. Mine site characteristics to be evaluated should include the land area available for algal culture and the availability of fresh water in case this is needed for dilution or top-up of culture media due to evaporation. The location and accessibility of any CO_2 sources (i.e., flue gas or other sources) nearby should be noted, as these may be useful for optimising the culture conditions via the addition of CO_2 to the growth media.

In the case of AMD remediation, the desired purpose of the algae biomass may be the neutralisation of the acidity, and removal of sulfate and metals. Treatment of heavy metals may require algae which are known to target and immobilise specific elements such as cadmium or copper (Xu et al., 2024). The recovery of specific metals such as lithium and gold may need species which allow the recapture of those metals, e.g., via adsorption onto extracellular polysaccharides or via adsorption onto negatively charged cell surfaces (Günan Yücel et al., 2021). If targeting soil improvement and erosion control, filamentous algal biomass may help to improve soil structure and encourage stability, along with fertility improvements to provide carbon and macronutrients (nitrogen, phosphorous and potassium) to allow the establishment of plant growth (Subashchandrabose et al., 2013). Each of these end goals requires the selection of appropriate algal species, a cultivation system to allow rapid, reliable growth and suitable harvesting and biomass processing methods. Once the target of the process has been identified, suitable algal species will need to be chosen.

Step 2: Selection of algal species

The criteria for selecting algal taxa for cultivation at mine sites include the ability of the algae to grow in untreated or treated mine water. Another critical factor is the tolerance of the algal taxa to the temperature range present at mine sites. Moreover, it is important that the algae do not produce toxins (like some cyanobacteria do) to minimise any environmental harm and risks to personnel from the algal cultivation. If the production of valuable compounds is of interest for developing sustainable bio-based supply chains, the ability of algae to produce valuable products e.g., lipids, proteins, carbohydrates or pigments may also be considered. It is to be noted, that naturally occurring algae may already be present at mine sites and may have a competitive advantage over introduced strains. Additionally, especially in Australia, it is important to consider any restrictions for the use of imported strains in open systems as detailed in import permits.

Selecting algae from an appropriate environmental or laboratory source may be a good start, however algal growth rate is also an important consideration. Algal productivity may be represented in grams of biomass produced per litre per day (see equation 1) or specific growth rates per day which relates to the doubling time of the algae culture (see equation 2). In addition to volumetric productivity expressed in units per volume of growth system, the productivity can also be reported per surface area of the cultivation system.

The equation to calculate biomass productivity (P_b, g L^{-1} d^{-1}) is:

$$P_b = \frac{X_f - X_i}{t} \quad (1)$$

Where X_f (g L^{-1}) is the final biomass concentration, X_i (g L^{-1}) is the initial biomass concentration, and t (d) is the time required for growth (Adapted from Chatsungnoen and Chisti, 2016).

The equation to calculate specific growth rate (μ, d^{-1}) is:

$$\mu = \frac{\ln\left(X_2/X_1\right)}{t_2 - t_1} \quad (2)$$

where X_1 and X_2 are the biomass concentrations (g L^{-1}) at times t_1 and t_2, respectively, within the exponential growth phase (Adapted from Chatsungnoen and Chisti, 2016).

Some examples of specific growth rates for algae in acidic growth media are shown in Table 2.

The pH values and nitrogen concentrations in the growth media are also shown. The nitrogen concentrations in these studies varied widely (6.6 - 280 mg N L^{-1}). Some of these examples used media intended to replicate the composition of AMD. The specific growth rates shown in Table 2 range from 0.05 d^{-1} to 0.77 d^{-1}. An outdoor wastewater microalgae culture study performed by Shayesteh et al. (2021) using agricultural wastewater found specific growth rates in the range of 0.14 - 0.76 d^{-1} which may provide a useful comparison. In this study a baseline growth rate of 0.37 d^{-1} gave an aerial productivity of 9.13 g m^{-2} d^{-1}. Higher productivity values of 0.76 d^{-1} were attained under conditions of pH optimisation using a CO_2 addition strategy maintaining the pH at 6.5. These improved growth conditions gave an aerial productivity of 19.2 g m^{-2} d^{-1}. There are very little data in the literature regarding growth rates of algae using actual mine water particularly at a large scale. This appears to be a significant gap in the current knowledge. Therefore, further laboratory experiments and pilot trials with selected algal species under more realistic conditions would be required to ascertain achievable growth rates and make more informed choices of which algae are more suitable for mine site applications.

Table 2: The productivity of some microalgae species with potential for acid mine drainage remediation.

Algal species	Growth media	Media pH	N (mg L^{-1})	Specific growth rate μ (d^{-1})	Reference
Chlamydomonas acidophila SAG 2045	Synthetic media for acidophiles with glucose added	2.1	280	0.50	Abiusi et al., 2022
Galdieria sulphuraria ACUF064				0.54	
Galdieria sulphuraria ACUF074				0.77	
Stichococcus bacillaris	Bolds Basal Medium for lipid production with CO_2 added	3.3	6.60	0.22	Olivieri et al., 2011
Stichococcus chodati				0.05	
Stichococcus cylindricus				0.19	
Stichococcus fragilis				0.20	
Stichococcus minor				0.20	
Stichococcus sequoieti				0.22	
Ulothrix gigas	Synthetic media to match AMD from Iran with added N	3.0-4.0	40.5	0.09	Orandi et al., 2012
Euglena mutabilis	Synthetic media to match AMD from Canada with high N and P	2.0-5.0	52.5	0.42	Olaueson and Stokes, 1989

Step 3: Identification of mine water treatment of amendment needs

Pretreatment of the mine water may be required to neutralise extreme acidic or alkaline water, remove contaminants, or amend the nutrient composition. Macronutrients such as nitrogen and phosphorous may limit algal growth if these are insufficient for the species and culture conditions. As discussed in section 2.1.1 'Algae and their growth requirements', the ratio of elements in algal biomass generally fits a consistent and predictable ratio. Iterative optimisation of the culture system may also involve adjustments to micronutrient levels if these are found to be inadequate or excessive for fine-tuning growth. Possible mine water pre-treatment technologies are discussed in more detail in section 3.1.

Step 4: Selection of algal cultivation systems

In the early trial stages several cultivation systems may be considered and tested. Smaller scale systems may be used for maintaining stock cultures of algae, whereas medium and large-scale systems may be used for scale-up. Culture systems may include open or closed systems and be based on suspended or attached growth. Algal cultivation systems are discussed in more detail in section 2.3.1.

Step 5: Selection of algal harvesting and processing systems

Selecting an appropriate algal harvesting process is critical to enable the use of the grown biomass and recovery of clean water for recycling or release into the environment. Testing the process may provide insight into which combinations of algal species and cultivation systems are most productive and effective. Depending on the end-use of the algal biomass, options for algal biomass dewatering and product extraction should also be assessed.

Step 6: End-product verification

Assessment of the final product yield and quality for intended application is important to determine whether the process has been effective at achieving the end goal and meeting the 'aim of process' which was determined at the first step. Moreover, if bioproducts for algae-based supply chains are extracted from the biomass, the suitability of the residual biomass for other applications can be evaluated and market price of the products reviewed. From a regulatory requirements perspective, ensuring that the end-products comply with relevant safety standards for their intended use is equally essential (see section 3.6).

Step 7: Process optimisation

Considering what has been learned at each of the six steps above, further targets for improvements may be identified which can be trialled during the next iteration to review the outcomes of the implemented changes. In some cases, trialling more than one alternative pathway at smaller scale may more quickly help pinpoint the best approach before moving on to scaling up culture volumes.

The early stages of developing an algal cultivation technology may involve much more trial and error, with anticipated changes of direction and unforeseen challenges. Not only is every mine site different due to geological factors, but also seasonal variations as well as process developments throughout the life of the mine site, need to be considered. Predation by zooplankton or unexpected climate conditions may cause a 'crash' in the algae culture which may require some skill and patience to overcome. Therefore, having an agile process to adapt to these changes will be critical for success. It is also worth noting that algal species selected will adapt and change over time. Fluctuations in pH or nutrient concentrations may cause unreliable growth for some species and affect end-product quality. However, the ongoing selection of resilient strains and ongoing acclimation should encourage greater affinity to grow in the target water.

2.3 Algal cultivation and harvesting technologies that could be applied at mine sites

Several algal cultivation and harvesting technologies have been developed and implemented at large scale across the world. The following sections outline some examples of algal cultivation systems and harvesting and cell rupture technologies.

2.3.1 Algal cultivation systems

The cultivation of micro- and macroalgae requires different system due to the different size of the cultivated organisms. Examples of laboratory, medium and large-scale cultivation systems are described below.

Microalgal cultivation systems
Laboratory equipment for microalgal culture maintenance

A simple laboratory fitted with microscopes and sampling equipment can provide a foundation to monitor growth rates and quality indicators of a healthy growing algal culture. Synthetic growth media and sterilisation equipment, along with a small illuminated indoor growing area can provide capabilities to maintain quality stock of selected microalgal species. Semi-solid agar infused growth media can allow for very slow growth suspension of algal stock culture, with storage time-frames of up to a year or more and little intervention required under appropriate temperature and light control (See Figure 8A). Quality algal cultures can also be sustained under moderate to slow growing conditions using small bottles of prepared growth media down to approximately 10 mL in volume, and a subculture maintenance schedule of approximately every five weeks or so (See Figure 8B). As required, these small volumes can be gradually scaled up through a series of larger indoor flasks, to develop sufficient quantities of algal culture to serve as inoculum for larger outdoor growth systems (See Figure 8C and Figure 8D).

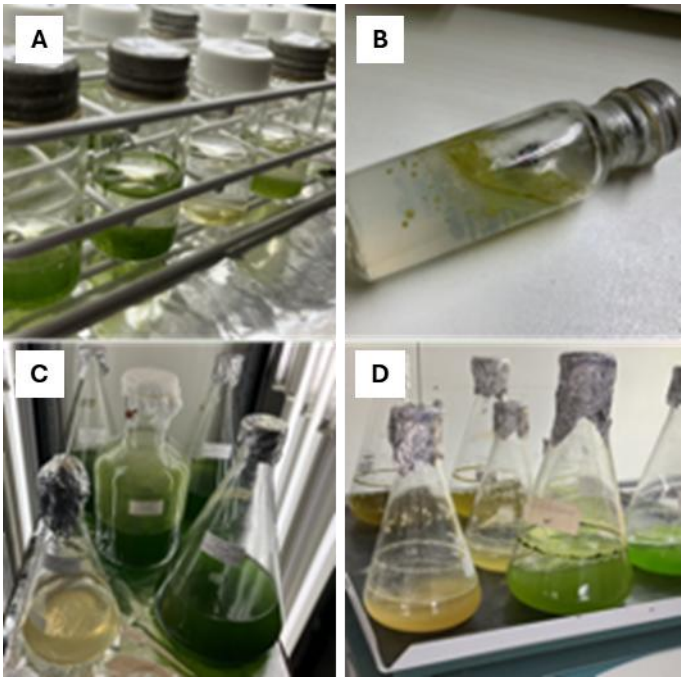


Figure 8: Small-scale micro-algal cultivation systems: A) semi-solid agar infused growth media; B) 20 mL vials with 10 mL liquid media; C) 2 L flasks on shaker plate; D) 5 L flasks on growth shelf.

Scaling up culture volume to prepare inoculum

The rate at which algae can double their biomass can vary depending on species from approximately several hours to one or more days (Chisti, 2007). This also depends on environmental light and temperature conditions, and nutrient availability in the growth media. To scale up a sample from tens of millilitres of stock culture to thousands of litres in volume can require quite variable timeframes and may take several months.

As an example of a microalgae, a stock culture of *Scenedesmus obliquus* - a species known for wastewater treatment potential, can have a growth of approximately 21 - 29% d^{-1} (i.e. doubling at approximately 3.5-5 d) at 20 - 30° C (Guedes et al., 2011). For an algae that has a doubling time of 5 d, it would take 140 d to scale up the culture from 10 mL volume stock culture to over 1,000,000 L volume of similar culture density (See Figure 9), assuming that the growth rate remains the same in the various sizes of culture systems.

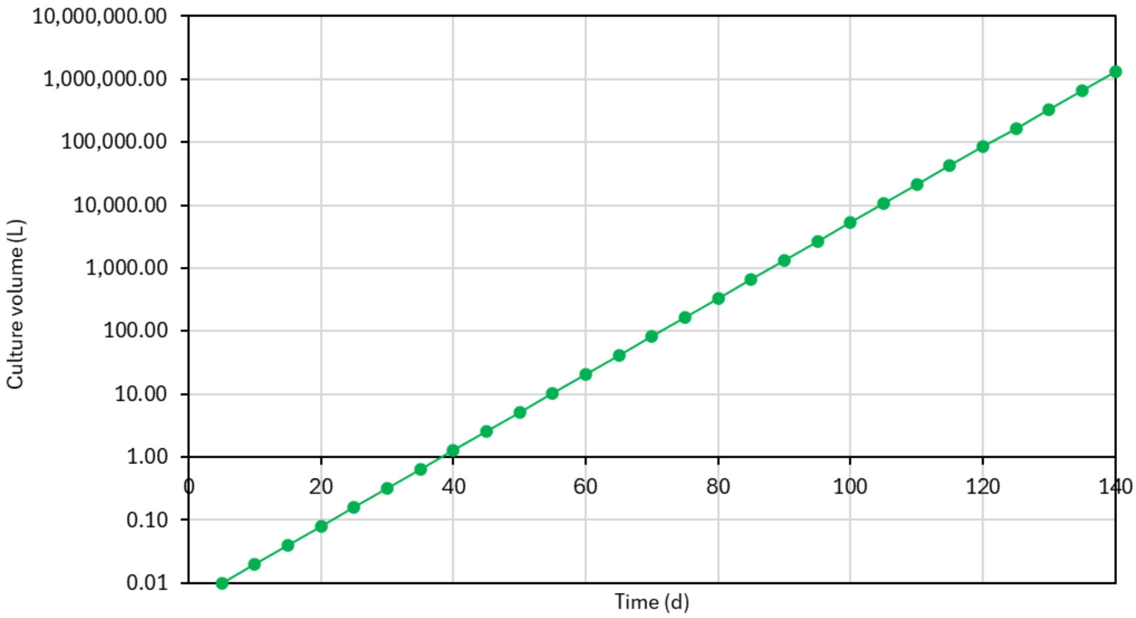


Figure 9: Scale up of culture volume for algal culture with a doubling time of 5 d.

Although the literature with regards to macroalgae is less extensive than microalgae, and growth media nutrient concentrations are typically lower than for microalgae, there may still be some potential for treatment of mining wastewater using macroalgae under appropriate conditions. For example, *Ulva lactuca* was grown in poultry litter extract using a pilot-scale flat-panel photobioreactor system, and sustained growth rates of approximately 20% - 30% d^{-1}, offering a growth rate comparable to the microalgae *Scenedesmus obliquus* example above (Mhatre et al., 2018).

Medium scale photobioreactor

Although culture volume can be increased in line with algal growth-rates, maintaining several medium scale culture volumes of several hundred litres may be useful to serve as ready-made inoculum when needed. These can also allow for more detailed study of algal growth habits and trialling of incremental optimisation which may be applicable to larger scale batch or semicontinuous cultures. These medium scale growth systems can be either smaller scale outdoor ponds such as raceway or other open pond designs (discussed in more detail below), or these could be closed or open photobioreactors which feature customised and more tightly controlled light and temperature conditions.

Several forms of photobioreactors have been studied and are in practical use at these medium culture scales (Figure 10). Some of these include: flat-plate, vertical column, stirred tank and aerated columns (bubble column and airlift) reactors (Assuncao and Malcata, 2020; Sirohi et al., 2022). Since the early 2000s tubular photobioreactors have been investigated. These have the advantage of taking up small land area, using vertical space more than footprint on land, and have a relatively short light path to allow good light penetration and good mixing of the growth media. These can be kept fairly well enclosed from the environment reducing the risk of contamination (Molina et al., 2001; Pirouzi et al., 2014; Nwoba et al., 2016; Nwoba et al., 2020).

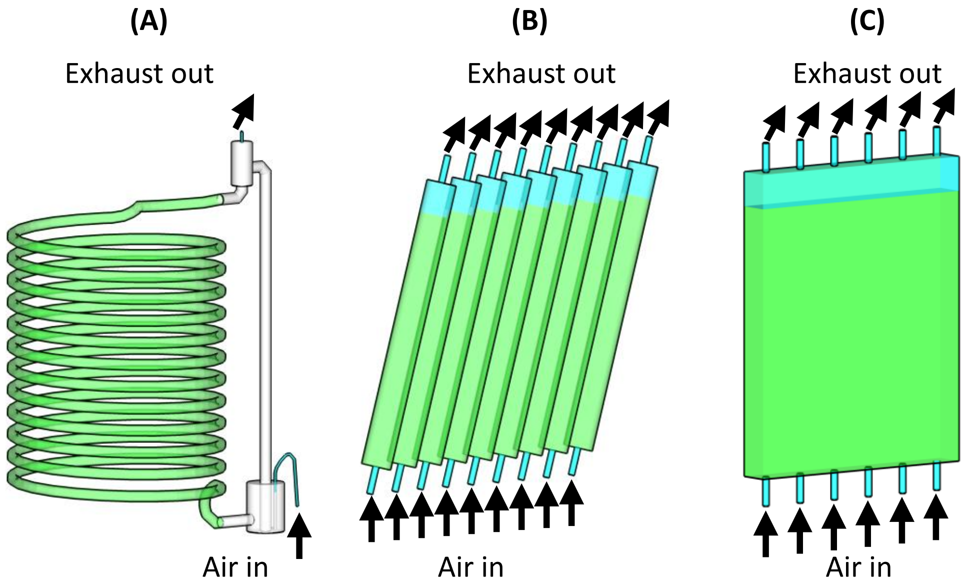


Figure 10: Schematic diagram of photobioreactor designs (A) a vertical spiral (Biocoil), (B) an inclined tubular column, and (C) a vertical flat-plate photobioreactor (Adapted from Muñoz and Guieysse, 2006).

Large scale microalgal growth systems

Australia is one of the best places for mass cultivation of algae as solar radiation is abundant, the climate is suitable for many algal species and seawater can be used to cultivate many algal species, whereas in many regions the land has low productivity for agriculture (World Bank Group, 2024). The large diversity amongst mine types and associated (waste)water compositions make it challenging to provide a one-size-fits-all solution. Algae are typically grown in different cultivation systems based on the product type (and value). Open raceway ponds, closed photobioreactors, floating bioreactors (Figure 11) and algae turf scrubbers could be considered for mining contexts.

Open raceway ponds require large flat areas for the construction of shallow ponds (i.e. ~25 cm deep) to cultivate microalgae in continually circulated nutrient-rich water. Although a very cost-competitive system in construction, inefficient use of light and CO_2 (thus limited productivities), evaporative losses, and dust and microalgae predator ingress represents the primary limitation for use of open systems. Internationally, operators have installed open ponds in low-cost poly tunnels to reduce evaporative losses and dust contamination, thereby enhancing product quality. This option could be considered within mining contexts if surface areas allow (Cuello et al., 2016).

Closed photobioreactors (PBR) of varying geometries represent high-end state of the art cultivation systems. These systems offer the advantages of increased illuminated surface area of the culture to maximise biomass production and quality (e.g., for human nutrition and pharmaceuticals), minimise CO_2 and evaporative losses as well as reduce contamination risk. However, they are more expensive than open ponds and are prone to heat stress due to the absence of evaporative cooling. This currently limits their application to producing biomass for higher value bioproducts (Cuello et al., 2016).

Floating photobioreactors: Floating PBRS represent a third viable alternative. These systems offer novel opportunities for microalgae cultivation on for example pit lakes, with the following benefits: 1) Earthworks can largely be eliminated as the floating system can be unfurled and floated onto the pit lake surface; 2) High illuminated surface area to volume ratios support increased biomass yields; 3) Increased CO_2 utilisation efficiency, 4) Reduced airborne contamination, 5) Minimise system overheating as the pit lake thermal inertia provides much more stable operational temperatures. As an added benefit it could also reduce evaporation from the pit-lake itself, reducing salinity increases and concentration of other contaminants in pit-lake waters (Cuello et al., 2016).

Algae Turf scrubbers (ATS) are systems designed to grow algae on a surface while treating water. They typically consist of a sloped or horizontal surface covered with a material that supports algae growth (Sutherland and Craggs, 2017). Water flows over this surface, providing nutrients and allowing algae to absorb pollutants and excess nutrients from the water (Adey et al., 2011; Adey et al., 2013). As the algae grow, they help clean the water and can be harvested for various uses (Ray et al., 2015; Salvi et al., 2021). ATS systems are valued for their simplicity and effectiveness in water treatment but may not match the productivity or control of PBRs and can be more expensive to construct compared to raceway ponds (Colosi, 2012). They do, however, allow for simple harvesting of algae biomass, which is often an energy intensive process for other cultivation systems (Siville and Boeing, 2020).

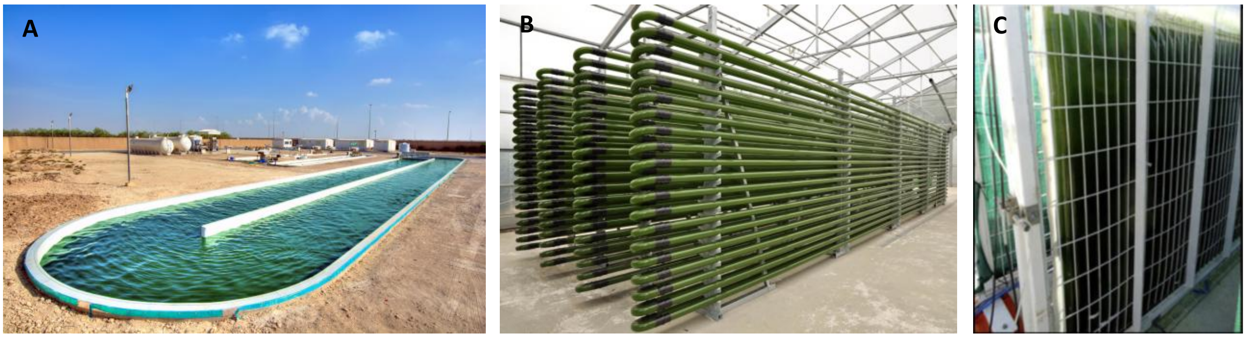


Figure 11: Large-scale microalgal cultivation systems: A) open raceway ponds (Qatar University); B) tubular closed photobioreactors (IGV Biotech); C) flat panel closed photobioreactors (University of Queensland).

The selection of appropriate unit operations is critical to the successful operation of the algal cultivation facility. Culture systems should be selected with consideration of factors such as light availability, temperature conditions, mixing requirements and the land available (Novoveska et al., 2023). The hydraulic retention time for the wastewater as part of a treatment process is also a consideration. It may not be possible to handle high volumes of growth media at one time, but rather a tightly-controlled semicontinuous growth mode or series of batch cultures may be a better option (Sutherland and Craggs, 2017). Various factors to be considered when selecting the appropriate culture system are shown in Table 3.

Table 3: Comparison of large-scale cultivation methods (Adapted from Novoveska et al., 2023).

Critical Factors	Open Ponds	Closed PBRs	Floating PBRs	Algae Turf Scrubbers
Land area required	High	Medium	Low	Medium
Predator/debris exclusion	No	Yes	Yes	No
Thermal regulation requirement	No	High	Low	No
CO_2 feed efficiency	Low	High	High	Low
Evaporation	High	Low	Low	Medium
Mixing energy required	Medium	High	Low	Medium
Additional light source	None	Yes	None	None
Volume throughput	High	Medium	Medium	Low
Cell density (for harvest)	Low	Medium	Medium	High
Contamination risk	High	Low	Low	High
Capital cost	Low	High	Medium	Low

Once the quality and purpose of the algal biomass product is understood, an assessment of capital expenditure (CapEx) and operating expenditure (OpEx) costs can be considered for a larger scale culture system appropriate for the volumes of water to be treated (Alavianghavanini et al., 2024). It is worthwhile keeping in mind the risks and challenges which need to be addressed to keep the system profitable or maintain the desirable outcome, and to handle the challenge of scaling up appropriately (Borowitzka and Vonshak, 2017). Even with a successful culture system operating efficiently, critical failures and excessive expense could arise if maintenance is not kept up or if the harvesting system fails (Rao and Henderson, 2022). Many of the risks can be mitigated through the careful selection of unit operations related to culturing and harvesting systems.

Macroalgal cultivation systems

Large scale macroalgae culture systems

Macroalgae cultivation systems can either utilise free-floating algae, or biomass adhered to the bottom of the water body or some kind of solid substratum (Millar, 2009). Examples of vertical and horizontal rope systems and long-line single raft systems and grid raft block systems are shown in Figure 12. In seawater, naturally occurring kelp forests of *Macrocystis pyrifera* can reach great depths, as long as sunlight can penetrate deep enough to sustain photosynthesis. Shallow marine environments can sustain delicate species such as *Gracilaria* sp. or *Eucheuma*, or fresh-water lakes and rivers may sustain more hardy varieties such as *Cladophora vagabunda*, *Oedogonium* sp. and *Spirogyra* sp. (Machado et al., 2014; Cole et al., 2016).

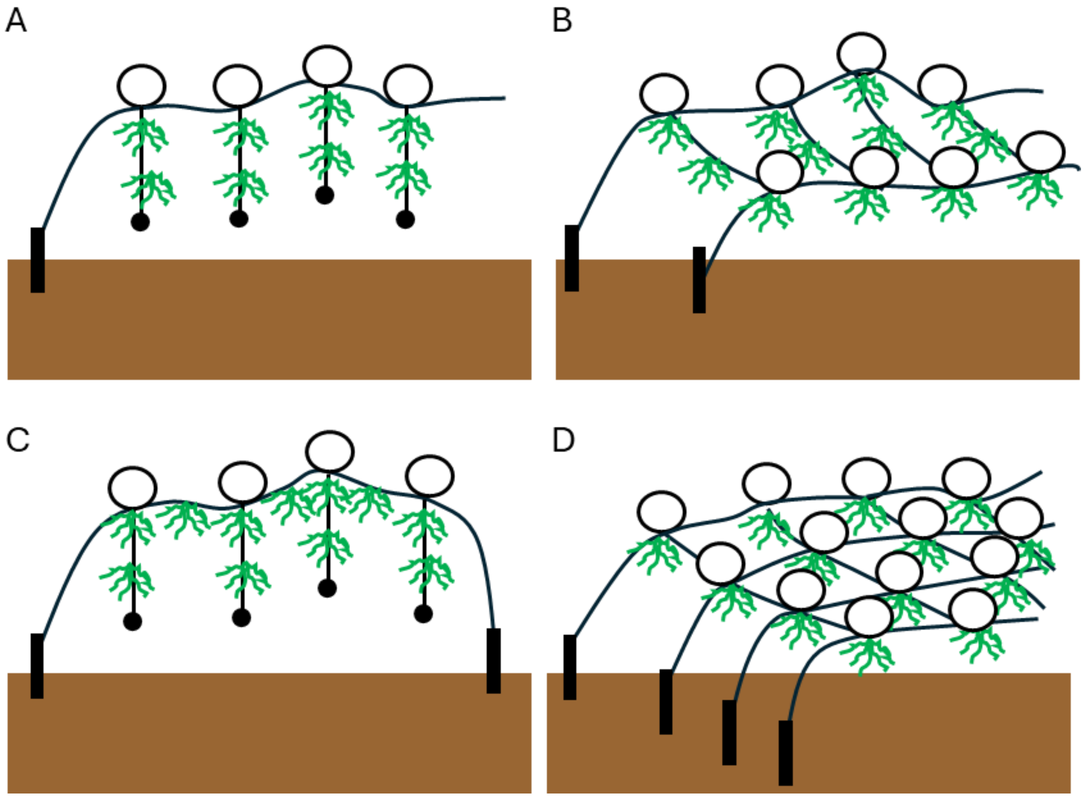


Figure 12: Examples of macroalgal growth systems: A) vertical rope system, B) horizontal rope system, C) long-line single raft system, D) grid raft block system (Adapted from Sharmila et al., 2021).

For the purpose of macroalgae culture to treat mining wastewater, it is unlikely that large off-shore facilities would be appropriate to receive the untreated water, unless a floating closed growth system could be used to retain wastewater during treatment. It is more likely that inland lagoons or waterways would be more suitable until the water is treated sufficiently to allow discharge. In these cases, fresh-water varieties (Lawton et al., 2017), or those tolerant to brackish water such as *Gracilaria* sp. may be the most suitable unless the mine water is saline (Mustafa et al., 2024). The culturing and harvesting systems should be suited to the species selected, which in turn should be tolerant and proven appropriate for the mine water quality available.

Free-floating species such as *Gracilaria* sp. or *Ulva* can be grown in gently moving, non-energy intensive culture systems such as a shallow lake or canal (Ryther et al., 1984). Most free-floating species originate from marine environments and may be sensitive to low salinity levels (Rybak, 2018; Ichihara et al., 2012), and may need specific temperature and nutrient conditions for optimal growth (Endo and Gao 2022).

Some filamentous freshwater macroalgae can be grown under conditions which favour an assortment of microorganisms such as microalgae, fungi and bacteria. These systems encourage a complex and diverse community of organisms and have a variety of names such as Algal Turf Scrubber® (ATS™), Filamentous Algae Nutrient Scrubbers (FANS) and Periphyton nutrient removal systems (PNRS) (Yun et al., 2015; Sutherland and Craggs, 2017). These growth configurations may include a concrete or compacted earth base sealed with impermeable membrane and attachment substrate (stalks, capsules, holdfasts or mesh-like materials) (Sutherland and Craggs, 2017). In these systems high-surface area corrugations and cobble-like mouldings allow for variance in water turbulence and gas-exchange areas which in turn allow the development of microhabitats to encourage high rates of surface colonisation by microorganisms and macroalgae. These systems have been trialled using domestic and agricultural wastewaters with some success at removing nitrogen, phosphorus and may be suitable for other contaminants such as heavy metals (Ellison et al., 2014; Sutherland and Craggs, 2017).

Sometimes macroalgae culture systems may be accompanied by other aquatic life. Investigations into aquaculture integration with macroalgae culture have found some success with the macroalgae using excess nutrients and providing cleaner water for the aquaculture system (Lavania et al., 2014; Copertino et al., 2008).

2.3.2 Algal harvesting technologies

Microalgal harvesting

Microalgal harvesting methods include centrifugation, tangential flow filtration, forward osmosis, flocculation, bioflocculation, dissolved air flotation, electroflotation and magnetic separation. Typical recovery rates, benefits and limitations of each of these methods are shown in Table 4. Parameters affecting the selection of the harvesting system include the naturally occurring tendency for the algal biomass to flocculate or settle easily, and whether additives are needed to encourage settling in the dewatering process. For instance, algal biomass which settles or flocculates easily may be more amenable to filtration, whereas algal species or conditions which tend to result in a suspended culture may require centrifugation which is a more energy demanding process (Rao and Henderson, 2022). Flocculants can be added to improve harvesting but may remain combined with the biomass which may affect the quality of the end-product. Downstream processing may be able to compensate for some, but perhaps not in all cases (Li et al., 2020).

Table 4: Microalgal harvesting methods, and their recovery efficiencies, benefits and limitations (Adapted from Difusa et al., 2015; Li et al., 2020). N/A = not available.

Harvesting method	Recovery (%)	Benefits	Limitations
Gravity sedimentation	N/A	Low cost, easy to operate, without contamination	Long operation time, limited to high density algae, low slurry recovery
Centrifugation	90	Reliable, high solid concentrate, high recovery efficiency, time-saving and efficient, strain independent	Energy intensive, expensive, special equipment required, high maintenance and operation costs, destroys cellular biomass
Filtration (e.g., tangential flow)	70-89	Reliable, high solid concentrate, high recovery efficiency, low energy consumption, low shear stress	Membrane fouling, high (operating) cost, limited by membrane size, time consuming, membrane replacement and pumping required
Forward osmosis	80-92	Low energy input	Slow, problems in reverse solute flux
Flocculation	80-95	Good recovery	Flocculants can be expensive, may cause contamination
Bioflocculation	90	Environmentally friendly	Environmental stress used for inducing bioflocculation may change cell composition
Dissolved air flotation	80-90	Proven in large scale, flexible, small space requirement, time-saving and efficient	Surfactant required, high energy consumption, oversized bubbles break up the flocs, the use of flocculants may create problems
Electroflotation	>95	Efficient recovery	High cost, electrodes need periodic replacement, metal contamination
Magnetic separation	90-98	Rapid, low energy input	Complex fabrication, expensive

Macroalgal harvesting

Macroalgal harvesting can be conducted either manually or through mechanical harvesting (Table 5). Manual harvesting can be performed using cutting tools such as blades or motorised cutters, e.g., from a boat. Manual harvesting has low energy requirement and is suitable for small water bodies. However, constant monitoring is required due to temporary effects, and care has to be taken to avoid possible venomous organisms and mine water contaminants. Mechanical harvesting can be carried out using amphibious vehicles, boats, land-based long-armed vehicles equipped with suction apparatus, rotating mowers, cutters, rotating blades and dredgers. Mechanical harvesting is good for large and deep water bodies and large algal quantities, but has high energy requirements (Alam et al., 2021).

Table 5: Methods for macroalgal harvesting (Adapted from Alam et al., 2021).

Method	Examples	Benefits	Limitations
Manual harvesting	Cutting tools (blades or motorised cutters) e.g., from boat	Low energy requirement; Suitable for small water bodies	Requires constant monitoring due to temporary effect Care needed against venomous organisms
Mechanical harvesting	Amphibious vehicles, boats, land-based long armed vehicles equipped with suction apparatus, rotating mowers, cutters, rotating blades dredgers	Good for large and deep waterbodies and algal quantities	High energy requirement

2.3.3 Cell rupture technologies

Whole algae biomass can be used as is for a number of applications (e.g., feeds, supplements, fertilisers), however, for certain products, especially valuable components (e.g., oils, proteins, pigments), cell rupture or "cell disruption" is a crucial step to break the cell walls and release the intracellular contents. Various cell rupture technologies exist, each with its own advantages, limitations, and scalability considerations for commercial use. An overview of relevant cell disruption methods for downstream processing of algal biomass is shown in Table 6.

Table 6: Overview of relevant cell disruption methods for downstream processing of algal biomass (Adapted from Günerken et al., 2015 and Lee et al., 2012).

Class	Name	Description	Scalability
Mechanical disruption	Bead milling	This method uses small beads in a mill to physically shear algae cells open. It is highly effective for microalgae with tough cell walls.	Can handle large volumes, making it scalable, but is energy-intensive, which increases operational costs, especially at larger scales.
	High-pressure homogenisation (HPH)	Algae are subjected to high pressure and forced through a narrow valve, creating shear forces that disrupt cell walls.	HPH is scalable and effective, particularly for liquid algae suspensions. It is commercially viable but also energy-demanding, making it more suitable for high-value products.
	Ultrasonication	High-frequency sound waves generate microbubbles in the algae suspension, which burst and create shear forces that disrupt the cells.	While effective, its energy consumption can be a limiting factor for large-scale applications, though it has potential in combination with other methods.
Chemical disruption methods	Solvent extraction	Organic solvents (e.g., hexane) penetrate cell walls and dissolve lipids, effectively rupturing the cells and extracting valuable oils.	Solvent extraction is scalable and commonly used in the industry. However, it requires subsequent solvent removal, and handling organic solvents poses environmental and safety challenges at scale.
	Osmotic shock	Placing algae cells in a highly concentrated solution creates osmotic pressure differences that cause the cells to rupture.	While less energy-intensive, this method is generally limited to small-scale applications due to low efficiency and potential nutrient loss.
Enzymatic method	Enzymatic lysis	This method uses enzymes to break down cell walls in a controlled manner. It is a gentle, effective approach for specific components.	Works well at lab and pilot scales, but high cost of enzymes and slower processing time make it challenging to scale, especially for bulk algae products.
Thermal disruption methods	Steam explosion	Algae are subjected to high-pressure steam, then rapidly depressurised, causing cells to rupture,	Steam explosion can handle large volumes and is scalable, but it can also degrade heat-sensitive compounds and requires significant energy input
	Microwave-assisted extraction	Microwaves generate heat within the cell, causing water to vaporise and build pressure until the cell bursts.	Microwave-assisted extraction is suitable for extracting heat-stable compounds and can be scaled up, though it also has relatively high energy costs.
Electrical and other emerging technologies	Pulsed electric field (PEF)	Short, high-voltage pulses are applied to the algae suspension, causing electric breakdown of cell walls.	PEF is a promising, scalable technology with relatively low energy consumption, and it preserves heat-sensitive compounds. However, PEF is still emerging and not yet widely applied at a commercial scale.
	Cationic polymer-coated membrane treatment	Algae suspensions are passed through membranes coated with cationic polymers where the positively charged polymer interacts with the negatively charged algal cell walls, weakening them and aiding in cell rupture as the cells pass through the membrane under pressure.	The high cost of cationic polymers and membrane replacement can be a limiting factor, especially as these membranes are prone to clogging over time with large algae biomass. Could however be promising with more optimisation.
	Laser-induced cell disruption	Laser methods use focused light energy to create localised heating, vaporising intracellular water and generating pressure that disrupts the cell walls.	Industrial applications is challenging due to the high energy requirements and lack of uniformity across larger volumes.
	Supercritical CO_2 extraction	Supercritical carbon dioxide is used as a solvent to penetrate cell walls and extract lipids and other valuable compounds	This method is scalable and efficient, particularly for lipids, and offers a green, solvent-free alternative. However, the high-pressure equipment is costly, which can impact commercial viability.

Effective cell disruption methods for industrial applications must balance energy efficiency, gentleness, selectivity, controllability, and universality. Mechanical methods, such as bead milling and high-pressure homogenisation, are currently the most widely used for large-scale applications due to their robustness and efficiency, although they consume substantial energy and often require intensive cooling to protect delicate compounds (Günerken et al., 2015).

Non-mechanical methods offer advantages in terms of energy efficiency and selectivity, but they tend to require longer processing times, larger treatment vessels, and chemical inputs, making control and waste management more challenging at scale. Emerging techniques, including pulsed electric fields and supercritical CO_2 extraction, hold promise for future scaling, especially for applications where environmental and energy efficiency are paramount. However, other experimental approaches, such as laser and pulsed electric arc methods, lack scalability, while innovative options like cationic polymer-coated membranes need further research to achieve effective cell disruption (Günerken et al., 2015).

Ultimately, no single method is universally optimal, and the best approach often depends on the specific product, the microalgae species, and the intended scale of operation. As a result, commercial microalgae processing often employs a combination of methods to balance operational efficiency, cost, and product quality.

2.4 Technologies for using algal biomass for beneficial uses in mining context

Micro- and macroalgae can be used for a range of beneficial applications at mine sites. These include carbon capture, water treatment, mine waste stabilisation, dust suppression, and mine site rehabilitation. Each of these applications are discussed in the following sections.

2.4.1 Carbon capture

As discussed in section 2.1.1 'Algae and their growth requirements' the stoichiometric C:N:P ratio of algal biomass is approximately 106:16:1, or a mass ratio of ≈ 41:7:1 (Redfield, 1934; Ketchum and Redfield, 1949). Carbon dioxide (CO_2) is 29% C by weight. Therefore, 3.5 kg of CO_2 provides 1 kg of C, which requires 0.18 kg N and 0.02 kg P when being stored as algal biomass (excluding what may be released by the algae as soluble compounds into the water). When considering the mass of other nutrients, 1 kg of C ends up as ≈ 2.14 kg dried algal biomass which includes ash, oxygen, N, P and micronutrients. Ash accounts for ≈ 0.30 kg of this mass (calculations based on figures in Ketchum and Redfield, 1949, see Table 7). Therefore, it follows that to produce 1 kg of dried algal biomass including ash, requires ≈ 1.6 kg CO_2, or excluding ash ≈ 1.9 kg CO_2. In phycology literature 1.83 kg CO_2 : 1 kg of algal biomass is the commonly quoted ratio (Chisti, 2007; Slade and Bauen, 2013). Well-performing microalgal raceway ponds can have a biomass production rate of 15–20 g m^{-2} d^{-1} as an annual average (Roles et al., 2021). Therefore, based on the carbon capture potential of 1.83 kg CO_2 : 1 kg of algal biomass, a 1 ha microalgae growth facility with an average productivity of 15-20 g m^{-2} d^{-1} would be expected to produce ~55-73 metric tons of biomass and sequester ~100-134 metric tons of CO_2 per year into the microalgae. In comparison, the CO_2 fixation potential of terrestrial plants is 10-50 times lower (Onyeaka et al., 2021).

Table 7: The content of ash, phosphorus (P), carbon (C), hydrogen (H), nitrogen (N) and oxygen (O) in some algal species (Adapted from Ketchum and Redfield, 1949).

Species	Dry weight (%)		Ash free dry weight (%)			
	Ash	P	C	H	N	O
Stichococcus bacillaris	9.61	2.10	53.82	7.09	6.62	32.47
Chlorella pyrenoidosa	11.94	2.69	54.89	7.64	7.70	29.77
Chlorella vulgaris	12.40	2.58	53.37	7.49	7.74	31.49
Scenedesmus obliquus strain 1	17.78	3.91	54.55	8.20	7.50	29.75
Scenedesmus obliquus strain 2	12.98	2.53	54.87	8.16	8.65	28.32
Scenedesmus basilensis	14.34	3.13	54.82	8.32	8.46	28.40
Nitzschia Closterium	19.52	1.03	54.98	7.49	6.67	30.86
Mean value	14.08	2.57	54.47	7.77	7.62	30.15

The concentration of atmospheric CO_2 is approximately 0.04%, and CO_2 along with ions of bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) which are associated with alkalinity, make up dissolved inorganic carbon (DIC) (Cole and Prairie, 2014). These DIC sources provide the C requirement for photoautotrophic species such as plants and algae (Iversen et al., 2019). Some microalgae can utilise both DIC and organic carbon sources and can function as heterotrophs taking up C under dark conditions without the aid of photosynthesis. The term mixotrophic can be used for organisms which can perform both heterotrophic and photoautotrophic carbon uptake. In the context of mining wastewater remediation, it is anticipated that the high concentration of mineral compounds and low levels of organic C sources will result in DIC being the most available C source for algae growth in mine water. Live algae applied to soil for the purpose of mine-site rehabilitation may have access to both DIC and organic carbon in the soil, in which case mixotrophic species may have an advantage (Subashchandrabose et al., 2013).

Concentrated CO_2 added to algae growth media can increase DIC and improve algal productivity. The pH of an algae culture tends to increase during periods of high photosynthetic activity (Craggs et al., 2012), and CO_2 can be added to lower the pH and bring it within a favourable range to optimise growth (Moheimani and Borowitzka, 2011; Shayesteh et al., 2021). A pH control system comprising of a pH sensor triggering the release of CO_2 as the pH gets too high can modulate the pH within a favourable range. Another approach may be to deliver CO_2 as a constant steady stream, or regular intermittent injection to the growth media (Sutherland et al., 2015). For example, Chunzhuk et al. (2023) found biomass growth rates up to 0.37 g L^{-1} d^{-1} for *Chlorella vulgaris* at 3% and *Chlorella ellipsoidea* at 6-9% CO_2 concentration in the airstream, which represented an increase of approximately 20% compared to baseline growth rates without CO_2 addition. Some studies have found that high levels (over 40%) CO_2 concentrations can inhibit algal growth (Deprá et al., 2020; Yang et al., 2023), although this may depend on species and the degree of acclimation to these conditions.

Although laboratory studies often use pure CO_2 gas to isolate the effect of CO_2 without interference from other variables, mixed gas streams rich in CO_2 may provide a cost-effective carbon source for larger scale growth systems. Two of these options include flue-gas obtained from combustion, and biogas - the methane rich gas from anaerobic digestion (AD) (Scarcelli et al., 2021; Rocher-Rivas et al., 2022). Under limited circumstances the biogas from AD may be available for use, however flue gas is likely more readily available in the context of mining operations. Stationary machinery utilising combustion engines may provide a carbon supply which can enhance algal growth. In some cases, additional CO_2 may not provide an advantage (Young et al., 2019) or may be only optimal at lower concentrations (Nad et al., 2023). Therefore, care must be taken to control the dosing as required. Strategies such as acclimation (Solovchenko et al., 2015), selection of suitable strains through a trial process (Wang et al., 2018) or even radiation induced mutation (Cheng et al., 2016) may also be useful to prepare strains with improved carbon-capture potential under high CO_2 conditions.

Carbon capture for mining related wastewater treatment might be aided by high alkalinity to increase available DIC and impede the growth of competitive eukaryotes and other microorganisms (Canon-Rubio et al., 2015). In fact, highly alkaline conditions have facilitated the growth of some of the earliest life on Earth: stromatolites - microbial mats dominated by cyanobacteria - which have left their traces in the fossil records since ≈3,500 million years ago (McNamara and Awramik, 1992; Suosaari et al., 2016). Along with cyanobacteria, carbonate sediments can be formed by actions of green algae such as *Nannochloris atomus* (Yates and Robbins, 1998). It is interesting to consider whether this could serve as a long-term carbon capture and storage mechanism to deposit carbon from wastewater into a more stable form. Further study may be needed to test this concept.

Algae can also play a role in facilitating carbon capture within soils. Nitrogen-fixing cyanobacteria have long been used to provide valuable N for crops such as rice (Dhar et al., 2015). However, recent efforts have progressed to quantify the impact of carbon cycling by microalgae within a variety of terrestrial soil environments (Yuan et al., 2012; Jassey et al., 2022). Some estimates suggest that approximately two thirds of carbon within forests is stored within soils and peat deposits below ground rather than forest canopy (Dixon et al., 1994). However, depending on soil management and applications of fertiliser such as phosphate, some carbon captured within the live microflora may be released again inadvertently (Cleveland and Townsend, 2006), making carbon storage within soil a dynamic feature requiring further study if hoping to achieve long-term storage timeframes.

When the algal biomass is used to produce biofertiliser, biostimulants and/or biochar for mine site rehabilitation, there may be potential to increase the total carbon sequestered by accelerating both soil carbon sequestration and plant biomass production (Antonelli et al., 2018; Rupawalla et al., 2021; Rupawalla et al., 2022; Levett et al., 2023). Rather than relying on living algal biomass for carbon capture within soils, the use of charred biomass from algal carbon capture can offer another attractive option. Within recent decades, studies of 'Anthropogenic Dark Earths (ADE)' or *terra preta (de Indio)´* from Central Amazonia have revealed localised regions of very deep dark soil with increased nutrient load, enriched organic matter along with biochar and archaeological artefacts dating to pre-Columbian timeframes (Glaser and Birk, 2012). These rich deep soils contrast the surrounding areas which tend to have shallower soil often relying on cycling of nutrients from leaf-fall and atmospheric deposition of elements such as P, K and N to maintain fertility (Van Langenhove et al., 2020). The discovery and subsequent study of these soils have led to much interest in biochar as the critical factor to encourage binding of nutrients, improved soil structure, adding organic matter and enabling long-term carbon storage. In Australia, aboriginal activity at particular locations has also been implicated in the formation of similar soil types called 'Cumulic Anthroposols' which feature characteristics comparable to the South-American counterparts with carbon dating showing organic carbon storage depositions in the range of 600 - 1600 years old (Downie et al., 2011).

Strategies that optimise carbon capture for mine water and site rehabilitation may involve a combination of these approaches, bringing together CO_2 addition from flue gas, addition of alkaline DIC from mineral wastewater, biochar production for long-term carbon capture and application of living algal biomass to soils to increase the dynamic C available for the soil microbial community and encourage the return of plants and wildlife. Hence, algal production at mine sites may, directly by carbon capture or indirectly via enhanced plant growth, offer greenhouse gas offsets, helping mining companies to achieve their 'net-zero' carbon emission targets (Levett et al., 2023). However, it is to be noted that most products from microalgae, such as food, feed, and fuels, would re-emit the captured CO_2 to the atmosphere during use and degradation, and as such the CO_2 captured during production would not qualify for carbon credits. On the other hand, the use of algae as a feedstock for biochar production and subsequent soil amendment could entrap carbon in a stable form for decades if not centuries (Heilmann et al., 2010; Sayre, 2010).

2.4.2 Water treatment

Algae can be used for mine water treatment through various processes. By harnessing the natural capabilities of algae and their syntrophic microbial partners (e.g., bacteria), various undesirable properties, or contaminants (e.g., acidity, nutrients, salts, metals, sulfate) can be alleviated or removed from the mine water. Algae-based treatment can be used in combination with other biotreatment methods where microorganisms work in symbiosis with algae cells for effective treatment. In the context of AMD treatment, algae can play various roles (Figure 13). These include acidity removal via natural alkalinity generation and metal hydroxide precipitation; nutrient removal; heavy metal uptake and sequestration; synthesis of soluble extracellular polymeric substances (EPS) as a carbon source for biological sulfate reduction; dead algal biomass as a nutrient for sulfate reducing bacteria; as well as desalination. Various algal strains, including *Anabaena, Chlamydomonas, Chlorella, Cladophora, Oscillatoria, Phaeodactylum, Scenedesmus*, and *Spirulina* species, have been studied for their potential in the bioremediation of acidic water (Bwapwa et al., 2017; Dean et al., 2019). Table 8 summarises various studies that explored the use of algae in AMD treatment.

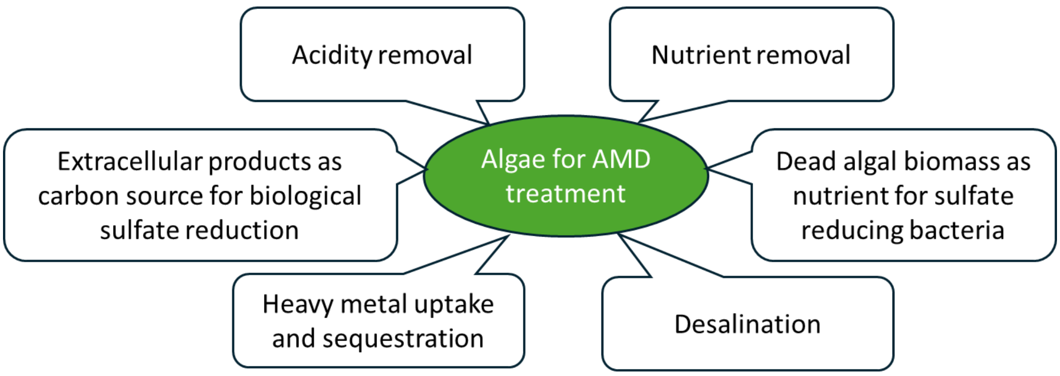


Figure 13. **Algae can facilitate acid mine drainage (AMD) treatment via various means.**

Table 8: Examples of application of algae for acid mine drainage (AMD) treatment (modified from Das et al., 2009). N/A = not available.

Algal species	Role in remediation	Result	System	Reference
Blue-green algae–cyanobacterial mat	N/A	Removal of 2.59 g Mn d^{-1} m^{-2}	Oxidation pond	Phillips et al., 1995
Spirulina sp.	Metal adsorption, re-alkalisation, nutrient for SRB (dead biomass)	(i) Removal of Fe (up to 100%), Zn (86–98%), Cu (38–76%), Pb (40–78%) at t_R of 10 d (ii) Rise of pH from 3 to 8.5 for a biomass loading of 3 µg mL^{-1} chlorophyll *a*.	High-rate algal pond (HRAP)	Rose et al., 1998
Spirulina sp.	Alkalinity generation & metal precipitation	(i) pH rise from 1.8 to 8.18 (ii) Reduction of SO_4 89%, Fe 99%, Pb 95%, Zn 93%, Cu 94%.	Bench Scale anaerobic digester, Primary and Secondary treatment	Van Hille et al., 1999
Mixed algal population	Soluble EPS as carbon source for SRB	Up to 57% of sulfate and 52% COD removal by mixed SRB	HRAP	Molwantwa et al., 2000
Eunotia exigua and *Pinnularia obscura*	Primary production	Chlorophyll *a* (Chl *a*) content 52–72 mg m^{-2}	Mining Lake	Koschorreck et al., 2002
Spirulina sp.	Dead biomass as nutrient for SRB	150 mg SO_4 removal g^{-1} algal biomass d^{-1}	Bench scale anaerobic up flow reactor	Boshoff et al., 2004
Blue-green algae (predominantly *Oscillatoria* spp.). – microbial consortium	SO_4 removal, metal precipitation by consortium	(i) pH increase from 2.93 to 6.78 (ii) Reduction of SO_4 29%, Fe 95%, Pb 88%, Zn 86%, Cu 97%, Co 83%, Ni 62%, Mn 45%	Bench scale test cell	Sheoran and Bhandari, 2005
Eunotia exigua and *Chlamydomonas* sp.	Enhance primary production thereby SRB growth	Reduction of Fe from 14 mg L^{-1} to 0.2 mg L^{-1} and SO_4 from 344 mg L^{-1} to 124 mg L^{-1}	Microcosm experiment	Fyson et al., 2006
Ulothrix	Metal absorption	Absorption of Cu 3500 mg L^{-1}, As 500 mg L^{-1}	AMD, Sar Cheshmeh copper mine	Orandi et al., 2007
Chlorella pyrenoidosa	Biodesalination	Maximum salinity removals in nutrient-supplemented coal mine effluent with HRT of 9 d: 93% in bubble column reactor and 92% in open raceway pond	Open raceway pond (35 L) and bubble column reactor (7 L)	Rawat et al., 2024

Alkalinity generation (acidity removal) and metal precipitation

During photosynthesis algae consume CO_2 which forms a weak carbonic acid (H_2CO_3) in water. The removal of CO_2 during this process reduces acidity and leads to an increased pH. Biogenic alkalinity may also be generated when algal biomass is used as electron and carbon source for biological sulfate, nitrate and selenate reduction (Kaksonen and Puhakka, 2007; Yan et al., 2021). These processes involve the microbial metabolism of algal-derived organic matter, which not only contributes to alkalinity generation but also supports the removal of various contaminants. This dual role highlights the potential of algae-based systems in water treatment applications. For instance, Van Hille et al. (1999) investigated the use of alkalinity produced by the alga *Spirulina* sp. in a continuous system and found that the alkaline environment created by the algal strain significantly promoted heavy metal precipitation in an AMD obtained from a storage dam at a copper, lead and zinc mine in South Africa. The system was designed to separate the algal component from the metal-containing stream to overcome metal toxicity to the algae. During the primary treatment process, over 99% of iron (98.9 mg L^{-1}) and 80–95% of zinc (7.16 mg L^{-1}) and lead (2.35 mg L^{-1}) were consistently removed over a 14-d period. Furthermore, the pH of the raw effluent was increased significantly from an acidic 1.8 to a neutral pH of over 7 in the treated stream, demonstrating effective neutralisation of the AMD. The secondary treatment and polishing steps were tailored to the specific characteristics of the effluent. For high-sulfate effluent, the treated stream was fed into an anaerobic digester. The combination of primary and secondary treatments achieved a remarkable removal efficiency (>95%) of all tested metals and reducing the sulfate load by 90% (Van Hille et al., 1999). This integrated approach highlights the effective use of algae in handling complex effluents while addressing both metal contamination and sulfate pollution.

Nutrient removal

Algae can assimilate nutrients such as nitrogen (N) and phosphorus (P) from water, thereby reducing the nutrient concentrations in water. This ability of algae is particularly useful in treating mine water that may have ammonium or nitrate from the use of explosives, or effluents from hydrometallurgical processes that use nitric acid and hence generate nitrate-containing effluents (Cheng et al., 2014). Unless removed, the excessive nutrient concentrations can lead to pollution and eutrophication in receiving water bodies. Algae can use various organic compounds containing nitrogen and phosphorus derived from their carbon sources. The assimilation of these compounds by algae leads to nutrient removal from the water, a process that typically takes a few hours to a few days (Lavoie and de la Noüe, 1985).

Bio-desalination

The use of algae for desalination represents a promising advancement for the treatment of saline mine drainage. Salt-tolerant algal species such as *Scenedesmus* sp., *Chlorella vulgaris*, and *Pheridia tenuis*, which naturally thrive in high-salinity environments like estuaries, are well-suited for addressing the unique challenges of mine water (Gautam and Kapoor, 2022). These halophilic algae not only tolerate saline conditions but can also absorb and concentrate solutes, reducing salinity levels effectively.

In a recent study, Rawat et al. (2024) validated an integrated approach using *Chlorella pyrenoidosa* (NCIM 2738) for treating nutrient-supplemented coal mine effluent (NSCME) while targeting desalination, heavy metal removal, and chemical oxygen demand (COD) reduction, alongside producing biomass and lipids for biofuel applications. The study evaluated *C. pyrenoidosa* cultivation in two pilot-scale reactor systems: a 10 L bubble column reactor (BCR) (58 cm height × 16 cm outer diameter × 0.5 cm thickness) and a 50 L open raceway pond (ORP) (80 cm × 35 cm × 26 cm). Both reactors were filled to 70% of their working volume with

NSCME. Microalgae cultivation was conducted in two successive stages: (i) batch mode until the stationary phase and (ii) semi-continuous mode at hydraulic retention times (HRTs) of 4, 6, and 9 d. Among these, HRT 6 d yielded the highest average biomass productivity of 950 mg L^{-1} d^{-1} in the BCR and 728.4 mg L^{-1} d^{-1} in the ORP. HRT 9 d facilitated maximum lipid production (1.8 g L^{-1} in BCR and 1.4 g L^{-1} in ORP) and the highest COD removal efficiencies (96.5% in BCR and 94.2% in ORP), as well as maximum salinity removal (93% in BCR and 92% in ORP). Fatty acid methyl esters (FAME) characterisation confirmed the biodiesel potential of the produced lipids, with a cetane number (CN) of 53.94 (Rawat et al., 2024). The results of this study underscore the immense potential of microalgae as an effective and sustainable solution for the desalination of mine drainage. By simultaneously achieving significant salt, metal, and COD removal, alongside the production of valuable biomass and lipids for biofuel applications, microalgae-based systems offer an integrated approach to addressing the environmental challenges posed by saline mine effluent.

Heavy metal uptake and sequestration

The process of heavy metal sorption by algae is inherently complex and generally involves two distinct stages (Bwapwa et al., 2017; Du et al., 2022). The first stage is extracellular sorption, which occurs rapidly and is considered a passive process (Du et al., 2022). This stage begins immediately after the algae come into contact with heavy metals and involves several mechanisms, including: the interaction between metal ions and anionic ligands on the cell surface; micro-precipitation; surface complexation; covalent bonding between metal ions and proteins or other polymers (Du et al., 2022). These mechanisms facilitate the initial capture of metal ions on the algal cell surface. The second stage is intracellular accumulation, which is slower than extracellular sorption and is an active, energy-dependent process. The mechanisms involved are highly species-specific and may include pathways such as phytochelation, where specialised biomolecules like phytochelatins bind and sequester metal ions to form stable complexes within the cell (Du et al., 2022). This stage not only enhances the algal capacity for heavy metal uptake, but also plays a protective role in mitigating metal toxicity.

The efficiency of heavy metal and sulfate removal by algae depends on multiple factors, including metal type, algal taxon, and the age of the biomass (Novis and Harding, 2007). Environmental conditions such as light intensity and temperature, which vary with seasons, significantly influence algal performance in contaminant removal (Elbaz-Poulichet et al., 2000; Brake et al., 2004).

The ability of algae to remove heavy metals also varies across strains. In general, green algae such as Chlorophyta and Phaeophyta demonstrate higher removal efficiencies than red algae (Rhodophyta) (Al-Shwafi and Rushdi, 2008). Additionally, dead algal biomass often exhibits greater metal adsorption capacity compared to living algae (Mehta and Gaur, 2005). For example, *Stigeoclonium* sp., a freshwater alga, has shown the ability to survive in mining water with high zinc concentrations (~10 mM) and effectively remove the metal (Pawlik-Skowronska, 2001).

Specific algal strains such as *Spirulina* sp., *Chlorella*, *Scenedesmus*, *Cladophora*, *Oscillatoria*, *Anabaena*, *Phaeodactylum tricornutum* have shown the capacity to remove a considerable amount of heavy metals from AMD. These strains act as "hyper-accumulators" and "hyper-adsorbents" with high selectivity for elements such as iron (Fe), cobalt (Co), zinc (Zn), molybdenum (Mo), and copper (Cu) (Bwapwa et al., 2017). These metals also serve as essential micronutrients, influencing enzymatic activity and cellular metabolism (Balzano et al., 2020; Nagarajan et al., 2022). Heavy metal removal can occur through one or a combination of two processes: biosorption, where metals are adsorbed onto the algal cell surface through mechanisms like complexation or micro-precipitation, and bioaccumulation, where metals are absorbed into the algal cells (Nagarajan et al., 2022). Both approaches demonstrate the potential of algae as effective bioremediation agents for heavy metal-contaminated water systems.

Microalgae for heavy metal-containing mine drainage

Algal remediation of heavy metals can involve live culture, or application of dead algal biomass to bind and retrieve these toxins. Live algal samples found in AMD impacted water (pH range 2.9 - 3.4) have been demonstrated to take up significant amounts of Al, Fe, Mn and Zn in the range of 14 – 46,000 mg kg^{-1} dry weight (Oberholster et al., 2014). There are many studies addressing this topic (Table 9). However, we have briefly discussed some of these relating to the heavy metal elements cadmium and copper to serve as examples which may illustrate the potential benefits and challenges for phycoremediation of this uniquely toxic group of elements.

Table 9: Algae used for heavy metal removal from AMD (adapted from Du et al., 2022).

Algal species	Growth method	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
***Klebsormidium* sp.**	Algae were collected from the mine site and grown in lab, Photo-rotating biological contactor (PRBC)	Cu 80–100, Mn 35–40, Mg 85–100, Ca 18–2, Ni 2.0–3.0, Zn 18–20, Na 20-25	Removal efficiency is 35%–50% by order Cu > Mn > Mg > Ca > Ni > Zn > Na	Orandi and Lewis, 2013
Oedogonium crissum	Field growth and laboratory experiment	Al 4.8, Fe 79, Mn 51, Zn 550	In all study pH conditions, *Oedogonium crassum* was considered to have the highest metal bioaccumulation rate	Oberholster et al., 2014
Klebsormidium klebsii				
Microspora tumidula				
Stichococcus bacillaris	Porous Substrate Bioreactor (PSBR)	Zn 2.0–3.0	Zn 15–19 mg g^{-1}	Li et al., 2015
***Sargassum* sp.**	Laboratory experiment	Cu 20, Cr 20	Cu 71.4 mg g^{-1}	Jacinto et al., 2009
Scenedesmus quadricauda	Laboratory experiment with dry biomass	Cr 100	Cr 58.5 mg g^{-1}, Cr 46.5 mg g^{-1}	Khoubestani et al., 2015
***Chlorella* sp.**	Stabilisation pond system	Zn and Pb 5.0–20	Zn 34.4 mg g^{-1}, Pb 41.8 mg g^{-1}	Kumar and Goyal, 2010
***Ulothrix* sp.**	Photorotating biological contactor (PRBC), algae collected from mine site	Cu 80–100, Ni 2–3, Mn 35–45, Zn 18–20, Sb 0.005–0.007, Se 0.03–0.04, Co 0.3–0.5, Al 0.07–0.09	The metal removal efficiency is 20–50% by order Cu > Ni > Mn > Zn > Sb > Se > Co > Al	Orandi et al., 2012
***Nephroselmis* sp.**	Pipe Insert Microalgae Reactor (PIMR), AMD pre-treated with active treatment	Fe 20.5 ± 9.8	Fe 24.2 mg g^{-1}	Park et al., 2013

Algal species	Growth method	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Spirogyra verrucosa	Laboratory experiment with dry biomass	Mn 50	Mn 40.7 mg g^{-1} (80.2%)	Bansod and Nandkar, 2016
Nannochloropsis sp.	Lab-scale growth, modified with silica and followed by coating with magnetite particles	Cu 6.4–64	Cu 56 mg g^{-1} (87.5%)	Buhani et al., 2021
Nannochloropsis oculata	Laboratory growth and experiment	Cu 16	Cu 99.9 ± 0.04% by metabolism and 89.3 ± 1.92% or 5 pg $cell^{-1}$ via adsorption	Martínez-Macias et al., 2019
Phormidium ambiguum	Algae isolated from River Nile and Ain Helwan Spring & Laboratory experiment	Cd, Pb and Hg are all 0.01	*P. typicum* had the highest removal efficiency of Hg 15.1 mg g^{-1}, Cd 5.5 mg g^{-1} and Pb 74.5 mg g^{-1}	Shanab et al., 2012
Pseudochlorococcum typicum				
Scenedesmus quadricauda var *quadrispina*				
Chlorella vulgaris	Lab-scale growth	Fe 788, Al 310, Mn 19.4	Removal efficacy for all metals reached approximate 99.9%	Brar et al., 2022
Spirulina platensis	Lab-scale growth and dried with 100 °C oven	Al, Ni and Cu 2.5–100	*S. platensis* Ni 95%, Al 87%, Cu 62%	Almomani and Bhosale, 2021
Chlorella vulgaris			*C. vulgaris* Ni 87%, Al 79.1%, Cu 80%	

Cadmium (Cd) has no known beneficial biological role and appears to be increasingly prevalent in various types of wastewater samples (Chandra and Kang, 2015; Khan et al., 2022), including AMD and gold mine wastewaters (van Dam et al., 2008). In some single cell organisms such as bacteria, yeasts and algae, several molecular strategies have evolved to resist the toxic effects of cadmium exposure. For instance, cation diffusion facilitator membrane bound proteins can move divalent ions such as Zn^{+2} and Cd^{+2} toward the cell exterior, whereas under some circumstances vacuolar (interior-directed) accumulation may be mediated by metallothionein proteins (Khan et al., 2022). These defence mechanisms, operating at the molecular scale, limit DNA or oxidative damage which might otherwise occur (Chiaverini and De Ley, 2010; Alquethamy et al., 2021).

Several microalgae species can grow under very high cadmium concentrations. For instance, *Chlorella* sp. could grow under conditions of 10,000 µg Cd^{+2} L^{-1} and remove 96% of the Cd^{+2} after 28 d of growth (Rehman and Shakoori, 2004) cited in (Khan et al., 2022). This starting concentration is approximately 2-3 thousand times the acceptable standard of 3-5 µg L^{-1} (World Health Organisation (WHO) and United States Environmental Protection Agency (US EPA) figures cited in (Maithani et al., 2023)), however with an impressive 96% decrease in concentration, the remaining ≈ 400 µg Cd L^{-1} would still remain well above water quality limits. This starting concentration of cadmium is within the (very wide) 101 - 163,800 µg Cd L^{-1} range published by Ighalo et al. (2022) for AMD wastewaters. Other species which have demonstrated removal of cadmium from wastewaters include *Tetraselmis suecica*, *Chlorella minutissima*, *Selenastrum capricornutum* and *Microcystis aeruginosa*, although in some of these cases the dead biomass was used as an adsorbent rather than as part of a live culturing process (Tripathi and Poluri, 2021). The combination of Cd remediation combined with cyanobacteria mediated N fixation was also explored in a study by Hu et al. (2022) looking at aiding rice production with promising levels of Cd removal.

Some interesting studies have explored the potential for biochar mediated heavy metal remediation. Some of these include algae or plant-origin biochar. Shen et al. (2017) studied the effects of a combined plant-origin biochar with a bio-polymer producing *Chlorella* sp. as a Cd removal agent, and found the synergistic effects enabled a maximum of 217.4 mg Cd(II) removed per gram of adsorbent. Cadmium removal from wastewaters using microalgae has been covered in more detail elsewhere in the literature (see Tripathi and Poluri, 2021).

Another heavy metal, copper (Cu), can be present in mining waste samples such as AMD in the range from approximately 3 - 149,700 µg L^{-1} Cu (van Dam et al., 2008; Ighalo et al., 2022) or bauxite refinery red mud leachate at approximately 200 – 2,000 µg L^{-1} (Sun et al., 2019a). Standards for surface water levels are approximately 1,300 – 2,000 µg L^{-1} (WHO and US EPA figures cited in Maithani et al., 2023). Although copper can be toxic in high concentrations as a water pollutant, it also has a role in biology at lower concentrations (Sunda et al., 2005). Copper treatments are also widely used for horticultural applications in a mineral form as a trace element supplement, and an apparent demand exists for alternative products which may fit organic farming methods (Katsoulas et al., 2020). Copper and zinc also serve in pork production to improve animal weight gain and provide resistance to microbial infection (Ding et al., 2021).

There are several studies looking at microalgae uptake of copper from wastewater samples with copper concentrations in the range similar to the mining wastes mentioned above, although we did not find research covering the extreme upper end of the AMD range. For instance, mine tailings water with a concentration of 408 µg L^{-1} Cu and a pH of 7.29 were able support growth of *Chlorella vulgaris* with up to 64.7% removal of Cu (Urrutia et al., 2019). Chan et al. (2013) reported up to ≈ 80% of Cu removal from a laboratory scale growth trial using microalgae *Chlorella vulgaris* and *Arthrospira maxima* (formerly called *Spirulina maxima*) grown on secondary effluent from a wastewater treatment plant with copper concentrations of ≈ 56,600 µg L^{-1} Cu, with both live and dead biomass providing similar copper removal although dead biomass was quicker at removal. Saavedra et al. (2018) studied the growth of a live culture of *Chlorophyceae* spp. under the influence of copper at concentrations of up to 6,000 µg L^{-1} Cu and reported 88% removal of the copper from the growth media. *Nannochloropsis oculata* was demonstrated to remove up to 99.99% of the copper from algal growth medium in the lower range of 3.2 to 16 µg L^{-1} Cu (Martínez-Macias et al., 2019). Orandi and Lewis (2013) showed a live-algal biofilm cultivation process dominated by *Klebsormidium* sp. using a photo-rotating biological contactor for the treatment of synthetic AMD and at pH 3 found removal of over 59% of Cu along with over 50% of other minerals including Na, Zn, Ni, Ca, Mg and Mn.

Recovery of valuable elements such as lithium and gold

Although lithium (Li) is only approximately 0.0035% of the Earth's crust (Teng et al., 2004), it is highly reactive and has unique chemical properties making it a valuable resource. Lithium mining is expected to grow dramatically in the decades ahead, with 59% of lithium product being used in the battery industry, and the remainder scattered across ceramics and glass (9%), lubricating greases (8%) and other industrial products (Meng et al., 2019). Lithium can be obtained from several natural sources, including brine deposits, such as those found in Chile and Bolivia (Kesler et al., 2012), however, the most abundant mineral called spodumene is chiefly found in Australia's pegmatite (igneous rock) reserves (Kesler et al., 2012; Asif et al., 2024).

Due to the recent rapid growth in lithium processing, there are few regulations established for guidance toward safe concentration levels in natural waterways or even drinking water (Adeel et al., 2023), although Australia does have a guideline of less than 2,500 µg L^{-1} Li for irrigation water (Australian and New Zealand Environment and Conservation Council (ANZECC), Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), 2000). Despite lacking regulations, microalgae mediated lithium recovery would maximise efficiency of the mineral resource and reduce potential for lithium run-off into natural waterways.

Recovery of lithium using the hypersaline tolerant microalgae *Dunaliella salina* was demonstrated to achieve 4,000 µg Li removal per gram of dry biomass, from a starting concentration of 20,000 µg L^{-1} under high pH of 9 growth conditions (Günan Yücel et al., 2021). This research revealed that the negatively charged cell surface was responsible for its affinity to bind the lithium ion. Experiments using other species such as *Chlamydomonas reinhardtii* and *Desmodesmus* sp. have also shown good recovery of lithium from industrial wastewater (Díaz-Alejo et al., 2021). Depending on appropriate quality controls, there may also be potential for lithium-containing food supplements mediated by microalgae culture, such as *Arthrospira platensis* which has shown ability to absorb low levels of lithium from its growth media (Liliana et al., 2021).

After iron ore, bauxite and lithium, gold ranks as one of the highest value mineral outputs for Australia, with Australia providing 10% of the world supply (Britt et al., 2017) cited in (Jang and Topal, 2020). Since the early 1850s, gold mining has significantly influenced Australia's economy, with steady improvements in technical capabilities geared toward more efficient recovery of this highly valued resource. Since the 1980s, a dramatic increase in gold production has occurred against the background of declining ore grade and increasing waste rock output (Mudd, 2007). Retired gold mines leave behind tailings reservoirs which can include minerals such as Cu, Zn and Al that can form AMD and put ground or surface waters at risk of contamination, with the degree of risk heavily influenced by rainfall patterns (van Dam et al., 2008). Separate from the remediation of AMD using algal treatment processes, recovery of remnant minerals including gold may be mediated by algal biomass bio-sorption processes. For example, defatted *Haematococcus pluvialis* biomass was shown to effectively recover Au from solutions of tetrachloroauric acid ($HAuCl_4 \cdot H_2O$) (Adhikari et al., 2024). Ju et al. (2016) investigated the recovery of precious metals from a wastewater solution containing metals copper (Cu), iron (Fe), platinum (Pt), nickel (Ni), zinc (Zn), tin (Sn), gold (Au) and palladium (Pd). By adjusting the pH to 0.3 ± 0.1 using nitric acid solution and applying approximately 7 mg dry algal biomass per mL of solution they achieved the selective recovery of over 90% Au and Pd while leaving other metals behind, in a process that took approximately 1 h or less and involved elution with an ammonium salt solution. *Nannochloropsis* and *Desmodesmus* have also been evaluated for their ability to adsorb Au. With an adsorption duration of up to 24 hours, an effective recovery strategy was identified, using 0.1 M thiourea (NH_2CSNH_2) in conjunction with 0.1 M HCl (Adhikari et al., 2023). Other algal species have been investigated for Au recovery such as *Lyngbya majuscula*, *Spirulina subsalsa* and *Rhizoclonium hieroglyphicum* (Chakraborty et al., 2008), and cyanobacterium *Plectonema boryanum* studied for its Au bioaccumulation properties (Lengke et al., 2006).

Biochemical oxygen demand (BOD) reduction

Elevated levels of biochemical oxygen demand (BOD) in mine wastewater can exhaust the dissolved oxygen concentration in the receiving water, leading to hypoxic or anoxic conditions that threaten aquatic ecosystems. These conditions can suffocate aquatic life and promote anaerobic processes, resulting in the accumulation of toxic byproducts such as hydrogen sulfide or methane (Kaloudas et al., 2021). Algae play a critical role in addressing these challenges by contributing to the removal of organic compounds that contribute to BOD. Through the process of photosynthesis, algae take up carbon dioxide and release oxygen into the surrounding environment. The released oxygen not only helps to replenish dissolved oxygen levels but also supports aerobic microbial communities, which are crucial for the oxidation and breakdown of organic matter. This synergistic relationship between algae and aerobic bacteria enhances the degradation of organic pollutants, thereby reducing BOD in the water (Abinandan et al., 2018; Muñoz and Guieysse, 2006).

Algae can form consortia with other microorganisms, such as bacteria, to create synergistic interactions that enhance the overall efficiency of wastewater treatment processes. This approach provides a comprehensive solution for addressing various pollutants. Algae-bacteria consortia, for instance, have been shown to significantly improve microalgal growth rates and pollutant removal efficiency (Mujtaba et al., 2018). A typical example of this synergistic relationship is seen in wastewater stabilisation ponds, where the collaboration between algae and bacteria facilitates efficient treatment. The success of these consortia, however, requires the optimisation of critical factors such as CO_2 concentrations, light intensity, and nutrient availability to support the growth and activity of both microorganisms (Chia et al., 2021).

Use of algal biomass as electron and carbon source for biotechnical mine water treatment

Algal biomass can also be used as an electron and carbon source for biotechnical mine water treatment. Depending on the mine water quality (e.g., acidic, neutral or alkaline) and the type of algae used (e.g., acidophilic, neutrophilic, alkalophilic) and the intended end-uses of algae, the algal cultivation can occur either before or after biological oxyanion, metal, metalloid and acidity removal as shown in Figure 14 (CSIRO background Intellectual Property (IP)). The biological oxyanion removal can include the reduction of e.g., sulfate, nitrate and selenate with sulfate-, nitrate- and selenate-reducing microbes to hydrogen sulfide, nitrogen gas and elemental selenium, respectively (Kaksonen and Puhakka, 2007; Yan et al., 2021). Biogenic alkalinity generated during sulfate, nitrate and selenate reduction can neutralise acidity (Kaksonen and Puhakka, 2007; Yan et al., 2021). Chalcophile metals, such as Cu, Zn, Ni, Co, Fe and Mn, and metalloids, such as As can be precipitated with biogenic sulfide (Kaksonen and Puhakka, 2007; Sahinkaya et al., 2017). Moreover, biogenic alkalinity facilitates the precipitation of metals such as aluminium as hydroxides.

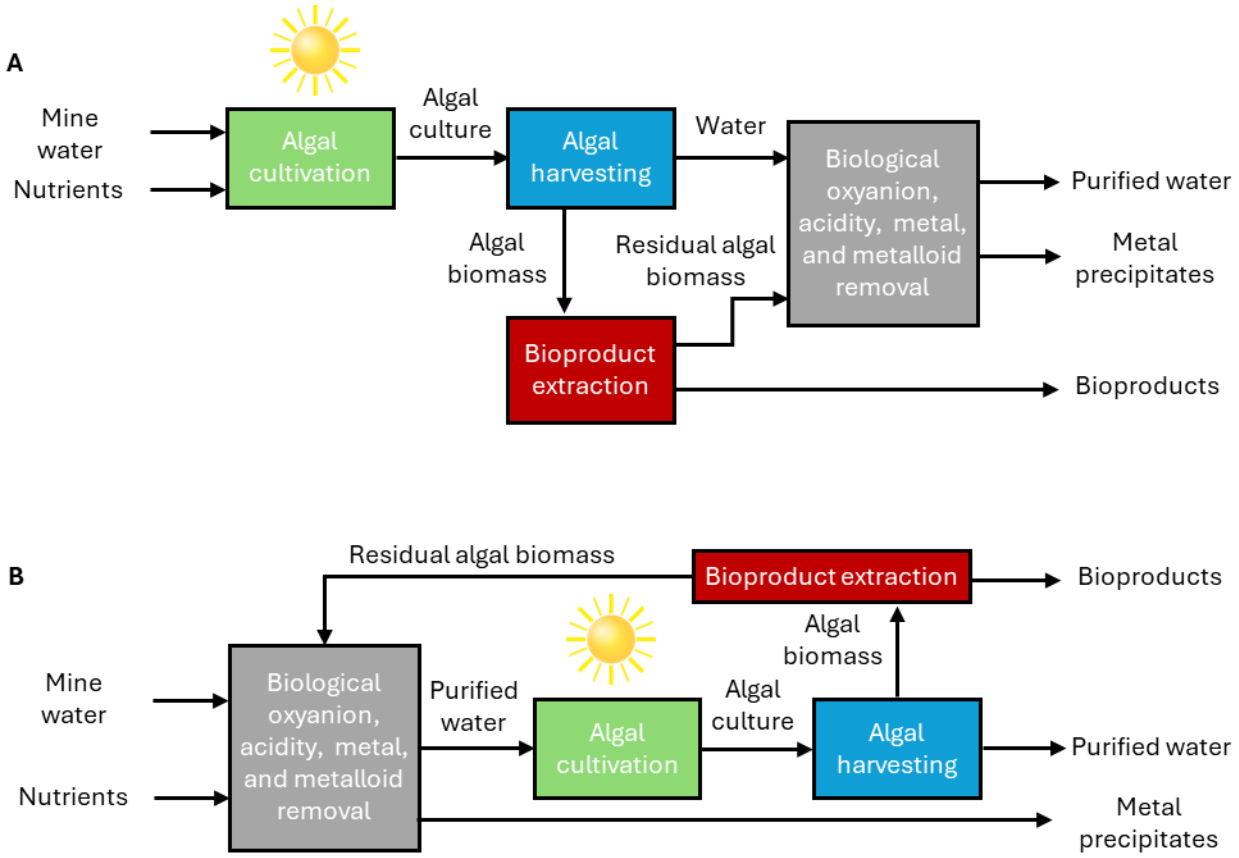


Figure 14: Options for integrating algal cultivation into mine water treatment. Courtesy of CSIRO (CSIRO background IP).

A) Algal cultivation before biological oxyanion, metal, metalloid and acidity removal where algae facilitate initial contaminant and acidity removal and serve as carbon and electron donor for subsequent biotechnical treatment; B) Algal cultivation after biological oxyanion, metal, metalloid and acidity removal, with algal biomass harvested, bioproducts extracted and residual algal biomass returned as electron and carbon source for mine water treatment.

2.4.3 Mine waste stabilisation

The two major environmental impacts of most mine wastes are the generation of acid mine/rock drainage (AMD/ARD) and the consequent release of hazardous and toxic elements (e.g., As, Se, Sb, Pb, Cd, Cu, and Zn), which is induced by the weathering of sulfidic mine wastes. AMD and metal leaching prevention is the key to avoid costly mine water treatment. The primary goal of prevention or source control is to stop contaminated drainage from leaving the mine site at its source by minimising reaction rates, leaching, and the subsequent migration of weathering products from mine waste to the environment. Minimising oxygen supply for pyrite oxidation, minimising water infiltration, isolating sulfide minerals, controlling pore water chemistry, neutralisation of acidity, and controlling bacteria and biogeochemical processes are among source control measures.

Effective stabilisation strategies are crucial to mitigate the release of harmful metals and acid into surrounding ecosystems. Various approaches have been proposed for mine waste stabilisation, including setting physical barriers to limit oxygen (O_2) transport into mine wastes (i.e., wet and dry covers), using bactericides to suppress the activity of bacteria that dominate sulfide oxidation, and stabilisation/solidification usually through chemical treatments, to change the physicochemical properties of mine wastes as well as the chemistry of surrounding environment (Wang et al., 2022b).

Mine waste stabilisation involves chemically reducing or eliminating the impact of hazardous waste by transforming solid contaminants into less harmful forms, while solidification focuses on encasing the waste in a solid material to eliminate contaminants (Punia, 2019). Therefore, the combined process of solidification /stabilisation (S/S) for mine waste includes mixing mine wastes with specific agents to make toxic pollutants non-toxic (Rey et al., 2020). The amendments used generally are either alkaline materials for acid consumption or compounds that react with the waste to restrict sulfide oxidation or bind metals in the reaction product (Li et al., 2019). Examples of alkaline materials include limestone, slaked lime (calcium hydroxide), fly ash, and alkaline paper mill waste, and examples of reactive compounds include phosphate, silicate, and sewage sludge (Herbert and Höckert, 2009).

Several types of covers, each with unique mechanisms and properties, offer promising solutions for mine waste stabilisation. According to Neculita et al. (2024) several mechanisms within amendments and covers made of organic or mineral, natural or residual materials can lead to geochemical and geotechnical stability of amended or covered tailings, including the following:

1. Consumption of oxygen and creation of a reducing environment favourable to the precipitation or preservation of metal sulfides in the presence of sulfate-reducing bacteria or Fe^{3+} to Fe^{2+} reducing bacteria.
2. Increase of pH and alkalinity of pore water, by addition of neutralising materials, or by mineralised organic carbon produced by final degraders, such as sulfate-reducing bacteria.
3. Dilution of contaminated pore water, and improved efficiency of passive treatment systems.
4. Formation of a hardpan layer of secondary minerals by neo-formed minerals precipitation playing a protecting role to prevent oxidation of unoxidised tailings.
5. Limitation of water infiltration in mine tailings by favouring horizontal runoff.
6. Improvement of geochemical and mechanical properties of tailings and development of a protective layer favourable to tailings revegetation.

Organic covers are increasingly used to control the generation of contaminated mine drainage from tailings storage facilities. Several organic materials, have been assessed as mine reclamation covers, including biosolids, industrial wastes, sewage sludge, composts, paper mill sludges, woody debris, and peat Rakotonimaro et al. (2021). Organic covers can be used as:

- an oxygen-diffusion barrier: a high degree of saturation of organic materials induces a low diffusion of oxygen in the material
- an oxygen-consuming cover: the decomposition of organic matter favours the depletion of atmospheric oxygen and dissolved oxygen in seepage water
- a cover with low saturated hydraulic conductivity: compaction and decomposition of organic cover may decrease hydraulic conductivity and water percolation.

Moreover, organic covers could increase the biological colonisation of mine soils (microbial activity and diversity, plant establishment) through the improvement of physicochemical properties (pH, nutrients, organic matter), as well as prevent water and wind erosion (Tassé et al., 1994). However, changes in the physicochemical characteristics of organic materials (e.g., total organic matter mass reduction associated with their degradation over time) could impact the long-term performance of the cover.

Oxygen-consuming covers

The Global Acid Rock Drainage guide (GARD guide, http://www.gardguide.com (The International Network for Acid Prevention, 2009) highlights several key solutions for mine waste stabilisation, focusing on the use of oxygen-consuming covers and innovative technologies. The GARD guide strongly advocates for oxygen-consuming covers as a primary method for reducing AMD. These engineered layers, placed over acid-generating materials like tailings and waste rock, limit sulfide mineral exposure to oxygen and water. Their effectiveness stems from several key mechanisms:

- **Oxygen reduction:** Microbial communities within the cover consume oxygen as they decompose organic materials (e.g., compost, biosolids, organic-rich sugar foam, cow manure). This creates an anaerobic environment that significantly inhibits sulfide oxidation, the primary driver of AMD. The study by Ribet et al. (1995) highlighted the importance of limiting oxygen exposure to sulfide minerals, emphasising that this limitation is crucial for preventing acid mine drainage and promoting the reductive dissolution of ferric-bearing secondary precipitates, which can lead to the release of metals from tailings.
- **Microbial activity:** The organics decomposition process not only consumes oxygen but also produces byproducts, such as organic acids, that further inhibit sulfide oxidation and reduce metal solubility. This buffering effect helps control pH levels, minimising the environmental impact. Koschorreck et al. (2011) demonstrated how the addition of whey to an acidic mine pit lake stimulated microbial respiration, consuming oxygen and creating anoxic conditions.
- **Moisture retention:** Maintaining adequate moisture is essential for microbial activity. Hence, covers should be designed to prevent saturation, which else could compromise cover effectiveness. The design should consider thickness, composition of organic materials, and hydrological control (proper drainage) to ensure long-term effectiveness (Levett et al., 2023).
- **Improvement of soil quality:** The addition of biosolids (e.g., municipal sewage sludge) to mine tailings also substantially increases soil carbon sequestration rates improving soil quality. This includes stabilising pH, increasing nutrient availability, and enhancing plant productivity (Antonelli et al., 2018).

Algal biomass derived from mine-influenced waters could be used as organic matter in oxygen-consuming covers and offers several advantages for mine waste stabilisation. Since organic matter within algal biomass is largely derived from atmospheric CO_2, its cultivation inherently represents carbon capture and utilisation (CCU). Further, the use of algae grown on-site utilising mine waters provides a cost-effective and sustainable solution, reducing the need for transporting external materials and aligning with environmental, social, and governance (ESG) objectives.

Long-term effectiveness of waste stabilisation

While a variety of cover options exist to stabilise mine waste, the choice of method depends on site-specific factors, cost considerations, and long-term management goals. Careful planning, including considerations of both biotic and abiotic interactions, is essential for ensuring the sustainable remediation of mine waste. The specific composition and design of covers should be carefully selected to meet the particular needs of the specific waste materials and environmental conditions.

The long-term effectiveness of any cover system depends on several factors, including biomass removal rates, where higher removal rates in oxygen-consuming covers reduce their oxygen interception capacity, potentially leading to increased oxidation and AMD generation. Further, over time, the degradation of the cover material itself can impact its effectiveness as a barrier to oxygen. Hence, regular monitoring and maintenance are crucial to ensure the long-term performance of any cover system.

There also exist some gaps in current research. While individual studies exist on oxygen-consuming biosolid, and monolayer covers, research on their combined use remains noticeably absent. This lack of investigation prevents a complete understanding of the potential synergistic benefits and optimal design configurations for integrated cover systems. Further research in this area is crucial for developing truly effective and sustainable mine waste remediation strategies.

2.4.4 Dust suppression

Dust generation in mines primarily occurs during operations such as drilling, blasting, and ore transportation. The mechanical processes involved in ore extraction break material into smaller particles, which become airborne during movement and handling. Some dusts, like coal dust, are hydrophobic and tend to remain suspended in the air, making control difficult. Wind and equipment movement can re-entrain settled dust, exacerbating the problem. This airborne dust poses significant health risks to miners (Liu and Liu, 2020) and causes environmental pollution, necessitating effective dust suppression strategies.

Common dust suppression methods include water sprays, chemical dust suppressants, and ventilation systems (Dong et al., 2023). Water sprays, a widely used technique, involve applying a fine mist or droplets directly to dust sources to capture and settle particles. However, their effectiveness is limited by environmental conditions like wind. Chemical dust suppressants, categorised as wetting (Wang et al., 2020), cohesive (Dong et al., 2023), or condensing (Sun et al., 2019b) agents, enhance dust control by binding particles or increasing moisture retention. Ventilation systems play a crucial role in diluting and removing airborne dust, improving air quality for workers and minimising dust accumulation (Dong et al., 2023). While these methods are often combined for improved efficiency, challenges related to environmental impact and cost remain.

Research on dust suppressants has evolved significantly from 1985 to 2021, shifting toward more environmentally friendly and effective solutions (Dong et al., 2023). Since 2012, there has been a marked increase in interest in new dust suppressants, particularly those prioritising ecological and environmental protection. This includes the development of compound dust suppressants, combining multiple mechanisms for enhanced efficacy, and the utilisation of sustainable materials. Since 2021, there has been a shift toward microbial, enzyme, and nanomaterial-based suppressants, driven by the potential to utilise waste materials in their production. Overall, the focus has shifted toward sustainable production of dust suppressants, reducing their environmental impacts (Dong et al., 2023).

Plant-based dust suppressants are currently emerging as a sustainable alternative to chemical dust suppressants. A prime example is the use of *Pinus elliottii* resin, derived from the southern yellow pine tree, which is being harnessed for its natural adhesive properties and environmental benefits. This resin is formulated into an effective dust suppressant by combining it with calcium chloride, water, ethanol, and γ-polyglutamic acid (γ-PGA), creating a solution that effectively agglomerates dust particles and prevents their dispersion (Campos et al., 2022). Similarly, sawdust has been demonstrated as a dust suppressant by transforming it into a super absorbent polymer through microwave-assisted chemical crosslinking with acrylic acid and 2-acrylamide-2-methyl propane sulfonic acid (AMPS) (Zhou et al., 2023). This polymer effectively absorbs moisture, binding dust particles together and preventing them from becoming airborne. Field applications in mining have demonstrated significant reductions in total and respirable dust levels, with average reductions of 90.07% and 85.43%, respectively. In this instance, the use of sawdust promotes waste recycling and environmental sustainability (Zhou et al., 2023).

In addition to these innovative approaches, other natural materials are also being explored for their potential as effective dust suppressants. For example, polysaccharide-based hydromulches have been identified as promising alternatives due to their ability to agglomerate dust particles while providing additional benefits such as moisture retention and weed suppression (Shcherbatyuk et al., 2024). These hydromulches, derived from natural sources like chitosan and glucomannan, can be applied using standard spray equipment, making them accessible for various applications. Field studies have shown that these materials can significantly reduce dust levels while also enhancing soil health (Shcherbatyuk et al., 2024).

Wang et al. (2023) in a recent study also revealed the prospect of using microalgae for the production of an environmentally sustainable dust suppressant. Microalgae can contain up to 80% oil by dry weight (Benedetti et al., 2018; Duarte et al., 2017; Singh and Singh, 2014), providing a significant source of raw material for the synthesis of dust suppressants. Microalgae oil, extracted through an optimised process involving solvent ratio, liquor-to-material ratio, and extraction time, serves as a novel, sustainable raw material for synthesising dust suppressants. The microalgae oil-based dust suppressant (MODS) is characterised as an amide dust suppressant and has superior hard water resistance compared to traditional anionic surfactants like sodium dodecyl benzene sulfonate (SDBS). This is attributed to MODS's ability to maintain stable interfacial properties even under varying temperatures, pH levels, and salinity, unlike SDBS which loses effectiveness in hard water. The MODS's excellent wettability, confirmed through contact angle and sinking time tests, highlights its potential as a greener, more effective alternative for specifically coal dust suppression in challenging mine environments (Wang et al., 2023).

Microalgal-based dust suppressants offer several advantages over traditional plant or other natural-based suppressants for dust management in mines. Firstly, microalgae have a significantly higher oil content, often reaching up to 80% of their dry weight (Benedetti et al., 2018; Duarte et al., 2017; Singh and Singh, 2014), which allows for more effective and concentrated formulations. Additionally, microalgae can rapidly grow and accumulate biomass while absorbing carbon dioxide, making them a sustainable and eco-friendly option. A notable prospect is the potential to cultivate microalgae using mine water, which may in some cases be rich in nutrients. This approach not only provides a valuable resource for dust suppressant production but also helps in treating and recycling mine water, thus addressing multiple environmental concerns simultaneously. Unlike many plant-based suppressants, which may have variable performance due to seasonal availability and differing compositions, microalgal extracts provide consistent quality and effectiveness. The high efficiency, sustainability, and reliability of microalgal-based dust suppressants position them as a superior choice for effective dust management in mining operations (Wang et al., 2023).

2.4.5 Soil amendment for mine site rehabilitation

Effective mine site rehabilitation hinges on growth media with key properties: stable, non-dispersive substrates promoting root growth, adequate water retention, and sufficient, vegetation-specific nutrients (Young et al., 2022). Essential indicators include infiltration and water holding capacity, aeration, and nutrient levels. Crucially, microbial communities, often overlooked, also play a vital role (da Silva et al., 2023). Nutrient depletion can affect revegetation by limiting germination, seedling establishment and long-term survival. Issues such as sodicity, low levels of essential nutrients (N, P and K), and low soil pH caused by the presence of acid forming materials are common in mine waste (da Silva et al, 2024).

Recent studies have proposed the conversion of mine waste into a soil-like substrate to enable vegetation colonisation and thus achieve resource utilisation, specifically, coal waste substrate modified by steel slag, sludge, or rice husk ash, successfully supported the growth of vegetation (e.g., Firpo et al., 2021). Various topsoil amelioration strategies can be used to promote mine site rehabilitation as shown in Figure 15. NPK fertilisation, gypsum addition and topsoil ripping are among the most common techniques used to ameliorate topsoil chemistry and structure in Queensland coal mines. The use of topsoil ripping, mulching, seed mixes/cover crops, and lime biosolids and fly ash addition have also been used to ameliorate topsoil as a growth medium. The incorporation of organic amendments such as compost, manure and different types of mulch has been used as an alternative technique to achieve revegetation goals during mine site rehabilitation. Compost may be beneficial to address surface mine restoration goals by improving important soil parameters, such as organic matter, labile carbon, nitrate content, and pH, that could lead to ecosystem recovery. The addition of a combination of lime and organic matter is capable of both increasing soil pH and favouring biological processes that increase organic matter cycling. Combinations of both strategies (gypsum and lime) with other common sources of ameliorants such as mulch, have been reported with positive outcomes in ameliorating both sodic and acidic environments (da Silva et al, 2024). Soil amendment with gypsum and NPK fertilisers improves chemical and physical properties for plant growth (Kumari and Maiti, 2022). External materials like ash or biosolids augment nutrient content. Mulching (organic or rock) enhances aggregate stability and organic matter content in topsoil. Topsoil ripping alleviates compaction, improving aeration and water infiltration. However, the effectiveness of each technique varies depending on site-specific conditions. While methods such as topsoil/spoil mixing with amendments provide short-term gains, long-term success demands site-specific approaches considering geological, ecological, and hydrological factors. This is particularly important in areas like the Bowen Basin, where prevalent clay soils with high pH negatively impact cation exchange capacity, soil fertility, and plant growth (da Silva et al., 2024).

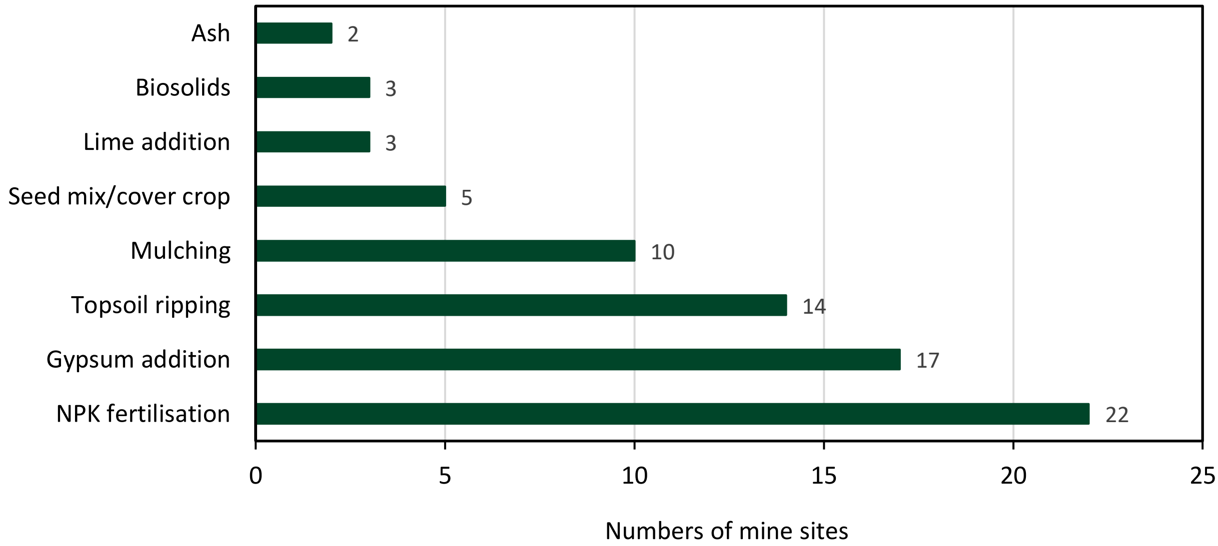


Figure 15: Current topsoil amelioration strategies used in coal mines in Queensland (Redrawn with data from da Silva et al., 2024).

While the techniques for addressing topsoil deficit in mine rehabilitation show promise, they also present several challenges. For instance, amendments like gypsum and fertilisers may provide only short-term benefits, potentially leading to nutrient leaching and diminishing soil quality over time (Pedrol et al., 2010). Moreover, excessive fertiliser use may decrease plant diversity in long term. Erskine and Fletcher (2013) suggest minimising fertiliser supplementation, particularly avoiding the application of large quantities of phosphorus to retain native grasses. The use of external materials such as ash or biosolids can introduce contaminants or imbalances in soil chemistry if not carefully managed. Municipal waste can present a risk due to the presence of solid contaminants, such as plastic and glass (Xiong et al., 2019). Emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) can be present in waste streams from landfills and wastewater treatment facilities (Heads of Environment Protection Authorities (EPAs) Australia and New Zealand, 2020). Contaminant risks require consideration before organic amendments from municipal waste streams such as biosolids, mulch and wastewater are used in rehabilitation. Additionally, mulching may require ongoing maintenance to ensure its effectiveness, and topsoil ripping, while beneficial for aeration, can disrupt existing soil structures and microbial communities. These challenges underscore the need for careful planning and monitoring to ensure that rehabilitation efforts lead to sustainable outcomes.

Carbon addition to mine tailings has been shown to enhance long-term rehabilitation success (Larney and Angers, 2012; Levett et al., 2023). Algae-based soil ameliorants can provide numerous benefits for soil health and plant growth. For instance, algal biomass can be used as biofertilisers, biostimulants and feedstock for biochar production. The use of onsite-generated algal biomass as an organic soil amendment presents several beneficial aspects for mine rehabilitation. Algal biomass is rich in essential nutrients, including nitrogen, phosphorus, and potassium, which can notably enhance soil fertility and promote plant growth (Figure 16). For instance, studies have shown that incorporating algal biomass can improve soil structure and water retention, leading to better moisture availability for plants, which is crucial in arid mining environments. Additionally, algal biomass can contribute to the restoration of soil microbiomes, fostering a diverse community of microorganisms that are vital for nutrient cycling and soil health. Repurposing excess algae from water bodies or acid mine drainage remediation provides a sustainable method for improving soil resilience and productivity in mined areas, thus contributing to successful rehabilitation (Levett et al., 2023).

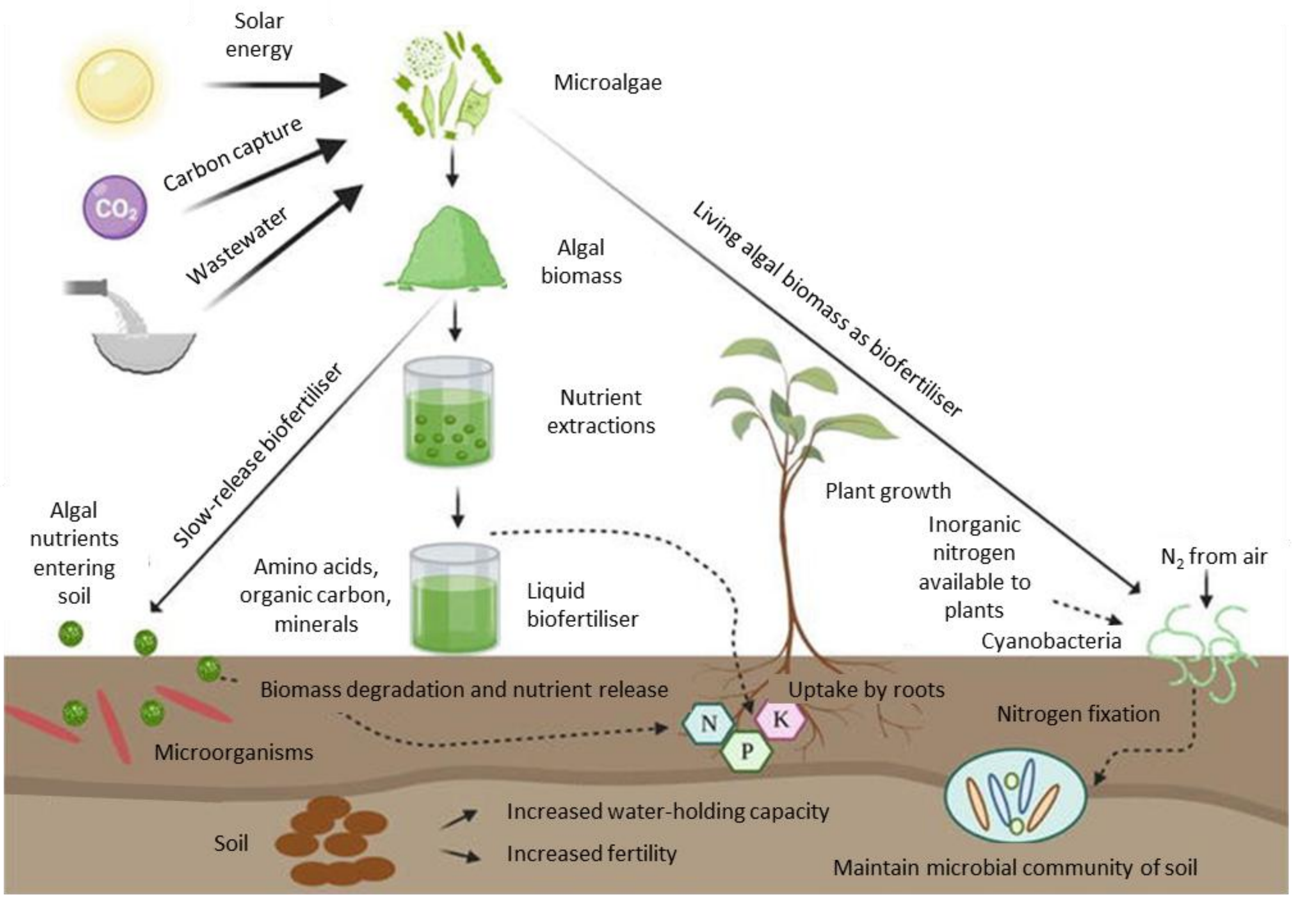


Figure 16: Microalgae-derived biofertilisers for soil improvement (Reused from Reisoglu and Aydin, 2023 with Creative Commons Attribution 3.0 License).

Biostimulants can improve plant resilience to stress, increase seed germination rates, and enhance plant development by providing growth-promoting substances and beneficial microorganisms. Algae-based biostimulants have been shown to scavenge reactive oxygen species, increase nutrient and water availability in the rhizosphere, and improve seed germination. Moreover, additional benefits include increased tolerance of plants to heavy metals, drought and salinity, and protection of plants from disease, hence enhanced plant viability (Levett et al., 2023). Some algae-based biostimulants have already been commercialised and are available in the market. One example is Microstart's Organic Liquid Kelp which is produced from Australian bull kelp, and has been reported to improve soil structure and aeration, plant respiration, nutrient absorption, disease resistance and soil water holding capacity, resulting in increased yields and plant resilience. Another product is the Ocean Magic from GreenPlanet, which is produced from Atlantic sea kelp and has been reported to support plant rooting and reduce environmental stress. Seaweed concentrate is used for example in propagation nurseries in Australia (Personal communication, 2024).

Microalgal biochar, produced through pyrolysis, also offers notable benefits for mine site remediation (Roberts et al., 2015a). Its high porosity, surface area, and stabilised nutrients improve soil aeration and water retention. According to Roberts et al. (2015a; 2015b), the incorporation of microalgae-based biochar into coal spoils has enhanced microbial nutrient cycling, boosting soil fertility and structure. Experimental trials have demonstrated improved trace element provision, faster grass germination, and increased plant biomass. Microalgal biochar thus contributes to ecological restoration and long-term sustainability of mine site rehabilitation (Roberts et al., 2015a; Roberts 2015b).

Overall, addressing topsoil deficits in mine rehabilitation requires innovative solutions. Utilising on-site generated algae offers a promising approach. Algae cultivation can provide a sustainable source of bioremediation agents, addressing nutrient deficiencies and improving soil structure, thereby mitigating the need for extensive topsoil sourcing and amendment.

2.4.6 Production of valuable commodities

Algal pigments

Microalgae are a promising source of high-value products, particularly pigments. They produce a wide variety of pigments, including chlorophylls (green), carotenoids (red, orange, and yellow), and phycobiliproteins (red and blue), often in concentrations substantially higher (one or more orders of magnitude) than those found in higher plants (Mulders, 2014). Additionally, microalgae offer the advantage of notably higher areal productivities compared to higher plants, making them an efficient and sustainable option for pigment production (Mulders, 2014). This potential makes microalgae an attractive candidate for industrial applications, especially when coupled with innovative systems for mine water treatment. Table 10 shows various commercially applied pigments that occur across most common microalgal groups. The pigments include various phycobiliproteins, chlorophylls and carotenoids. Some types of chlorophylls occur in all of these microalgal groups, whereas some types of pigments mainly occur in specific types of algal groups (Mulders, 2014).

Algal and cyanobacterial pigments can be used for a large range of applications. Some examples of these include fluorescent probes, molecular assays, textiles and cosmetics. Depending on the purity of the extracted algal pigments, they may also be suitable for use for colouring aquaculture feeds, foods, nutraceuticals or pharmaceuticals (Figure 17) (Deepika et al., 2022).

Table 10: Commercially applied pigments across most common microalgal groups (Data from Mulders, 2014).

Pigment group	Pigment	Cyanobacteriota (Blue-green algae)	Chloro-phyta (Green algae)	Eugleno-phyta	Green dinophyta	Glauco-phyta	Rhodo-phyta (Red algae)	Crypto-phyta	Bilin-dino-phyta	Peridinin-dino-phyta	Chryso-phyta (Golden algae)	Bacillario-phyta (Diatoms)	Hapto-phyta	Fuco-xanthin-dino-phyta
Phycobili-proteins	Phycocyanin													
	Phycoerythrin													
	Allophycocyanin													
Chloro-phylls	Chlorophyll a													
	Chlorophyll b													
	Chlorophyll c													
Carotenoids	Lutein				Some									
	α-carotene													Some
	Lycopene													
	β-carotene													
	Zea xanthin													
	Antheraxanthin										Some			
	Violaxanthin										Some			
	Neoxanthin													
	Diadinoxanthin										Some			
	Diatoxanthin										Some			
	Dinoxanthin													
	Fucoxanthin													
	Peridinin													
	Cantaxanthin	Some	Some											
	Astaxanthin		Some											

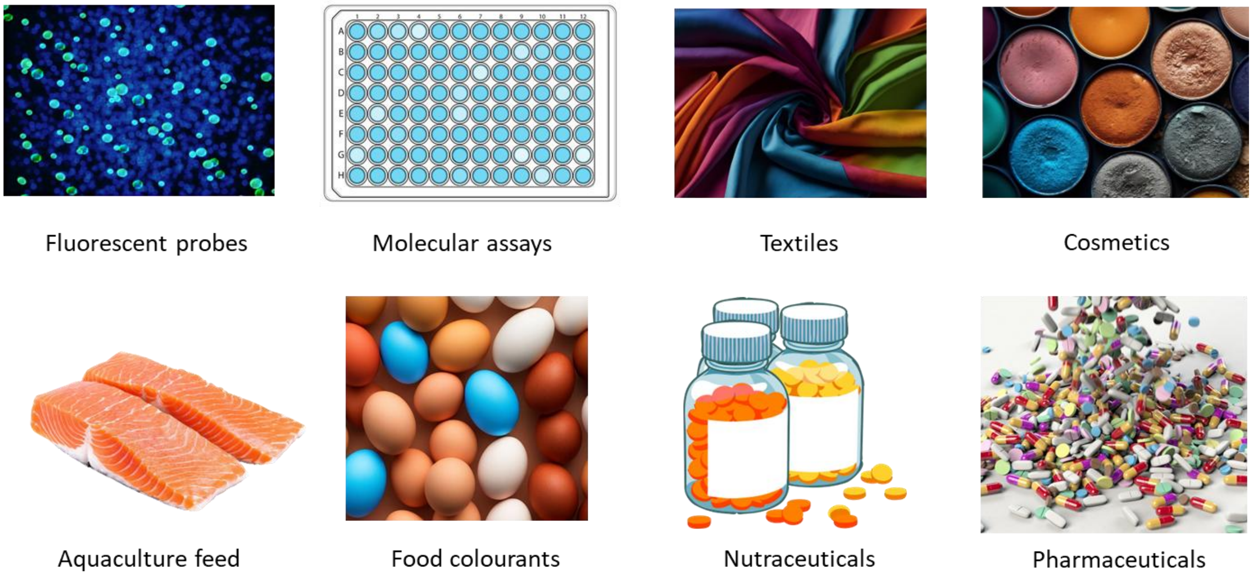


Figure 17: Examples of applications of algal pigments (Information from Deepika et al., 2022).

Despite the growing interest in utilising wastewater for algal cultivation, there are limited reports on algal pigment production at mine sites. While algae-based systems have been explored for wastewater treatment in mining operations (Section 2.4.2), the co-production of valuable pigments remains largely underexplored. Integrating algal cultivation for pigment production with mine site wastewater management represents a significant research gap that warrants further investigation. Addressing this gap could create sustainable pathways for mitigating environmental challenges while generating high value bioproducts, aligning with circular economy principles.

Recent advancements by Pérez-Roa et al. (2024) have provided insight into this potential, demonstrating the use of mining effluents to cultivate microalgal and cyanobacterial biomass for obtaining valuable compounds, such as red carotenoids and blue phycocyanin pigments. Two strains, Osci_UFPS01 (a cyanobacterium) and Chlo_UFPS01 (a microalga), were isolated from a hydrothermal source in Norte de Santander, Colombia and cultivated in mining wastewater mixed with BG-11 medium for Osci_UFPS01 and Bold Basal medium for Chlo_UFPS01. Optimal conditions for phycocyanin production were determined using response surface methodology (RSM), resulting in yields of 45% phycocyanin per unit dry weight and 1.1% (w/w) carotenoids in the mining wastewater mixture (Pérez-Roa et al., 2024).

Despite these promising results, studies investigating microalgal cultivation specifically in AMD media are scarce. Expanding this body of research could further enhance our understanding of the potential for algal pigment production using mine wastewater, offering innovative solutions to both environmental and industrial challenges.

Algae-based bioplastics

Algae have emerged as a promising feedstock for bioplastics production (Noreen et al., 2016). Unlike conventional feedstocks such as agricultural crops, algae can thrive under diverse growth conditions, including nutrient-limited and non-arable environments, and even in wastewater (López Rocha et al., 2020; Rajpoot et al., 2022). This adaptability makes algae a sustainable and versatile resource for bioplastic production, reducing the reliance on freshwater and arable land while potentially aiding in wastewater treatment (Rajpoot et al., 2022). The integration of algal systems with mine water treatment also creates a circular economy approach, where nutrients from mine water are recycled into algal biomass used for bioplastics, minimising waste and enhancing resource efficiency.

One of the key advantages of algae lies in their biochemical composition, which includes a wealth of natural biopolymers such as polysaccharides, proteins, and lipids. Table 11 summarises various algae-based biopolymers and their physical-chemical properties and applications. Algal polysaccharides have attracted significant attention due to their diverse structures and functional properties. Examples include alginate, fucoidan, agar, carrageenan, and ulvan, which exhibit excellent film-forming abilities (Yap et al., 2023). These films possess desirable characteristics such as high biodegradability and effective preservation properties, making them suitable for applications in packaging and other industries (Dang et al., 2022; Yap et al., 2023). In addition to polysaccharides, algal proteins and lipids also represent valuable feedstocks for bioplastic production. Proteins can be processed to form biodegradable films and composites with high tensile strength, while lipids can be converted into biopolyesters such as polyhydroxyalkanoates (PHAs), which are known for their excellent mechanical properties and environmental degradability (Yap et al., 2023).

Table 11: Algae-based biopolymers with their physical-chemical properties and applications (adapted from Yap et al., 2023).

Algae-based biopolymers	Properties	Applications
Carrageenan	• Water-soluble hydrophilic colloid polymers. • Dispersion happens at about 80°C, and chains attain random coil conformation on cooling at 40–60°C and forms coil-to-double helix conformational transition. • Strongly anionic, forms a gel in the presence of cations with helix–helix aggregation. • Different ester sulfate contents affect the properties of carrageenan (solubility, gel formation, viscosity).	• Food application • Pharmaceutical formulations • Cosmetics applications • Industrial applications
Agar	• Insoluble in cold water. • Dissolution when heating at 85°C and forming random coil conformation. With cooling to gelling temperature at 33–45°C, forming sol–gel transition that is double helical association. • Viscosity at 45°C is not affected by ionic strength or pH in the pH range between 4.5–9.0. • Gelation temperature of agar depends on the degree of methoxylation, when low methoxyl substituted fraction exhibit high gelling capacity.	• Food applications • Pharmaceutical • Cosmetic • Medical • Biotechnology industry
Algal protein	• Amino acid composition might be different but there is limited research on the algal protein quality between different algae species. • Their properties such as digestibility required to incorporate in vivo experiments.	• Human nutrition • Industrial application • Animal feed • Aquaculture
Alginate	• Charged polysaccharide with electrostatic forces from carboxylic groups. • Solubility varies on the pH and ionic strength of solvent. • High content of G-blocks form tightly held junction zones in the presence of divalent cations (Ca^{2+}) and form high gel strength.	• Food applications • Pharmaceutical applications (drug encapsulation)
Funoran	• Containing galactose, sulfur, 3,6-anhydro-ʟgalactose, uronic acids and acetylated residues depending on different species. • Funoran forms a thermoreversible gel in the presence of inorganic cations. • Soluble in cold water.	• Food applications • As consolidant for matte paint • Medical applications (blood anticoagulant) • Cosmetic industry
Cellulose	• Tough, water-insoluble. • High tensile strength of 62–500 MPa and elongation of 4%. • Hydrophilicity, chirality. • Having different degree of crystallinity depends on cellulose sources and affect their functionality. • Cellulose derivatives such as methylcellulose, microcrystalline cellulose, and microfibrillated cellulose	• Food applications • Paper production • Plastic processing industries • Pharmaceutical applications
Fucoidan	• Soluble in water. • Fucoidan has hygroscopic properties, but it does not form highly viscous solutions. • Chemical composition is different between brown seaweeds, fucoidan is mainly made up of fucose and sulfate, but also contain monosaccharides.	• Nutraceutical delivery systems • Pharmaceutical application • As functional food

Ulvan	• Ulvan mainly comprises sulfate, rhamnose, xylose, and glucuronic acid. • Ulvan has molecular weights ranging from 5.3×10^4 to 3.2×10^5 g mol^{-1} (depending on their species). • Their viscosity decreases under shear rate increase (pseudoplastic behaviour). • Intrinsic viscosity in saline solution of Ulva extract, even in high concentrations 95–285 mL g^{-1}. • Gelation can happen in the presence of suitable cations in a favourable pH.	• Biomaterial science (tissue engineering etc.) • Nutraceuticals application • As functional foods
Polyhydroxybutyrate (PHB)	• PHB are thermoplastic, hydrophobic, high crystallinity, brittle characteristics and biodegradable. • Common degree of crystallinity of PHB is 50% to 60%. • Their tensile strength at 20–40 MPa; elongation at break at 5–10%.	• Environmental applications • Packaging • Veterinary • Medical application

Algae-based bioplastics offer a wide range of applications across various industries (Rajpoot et al., 2022), as illustrated in Figure 18. In agriculture, these bioplastics are used to create biodegradable mulch films and seed coatings, which enhance crop growth while reducing environmental waste. Their natural antioxidant properties make them suitable for packaging materials that preserve food freshness and extend shelf life. In the medical field, algae-based bioplastics are being explored for applications such as wound dressings, drug delivery systems, and biodegradable implants due to their biocompatibility and non-toxic nature. Emerging technologies like 3D printing have also adopted algae-based bioplastics for the fabrication of sustainable, lightweight, and customisable components. Additionally, their film-forming and biodegradable properties make them ideal for food packaging applications, contributing to reduced reliance on conventional plastics and advancing sustainable packaging solutions (Rajpoot et al., 2022).

Algae-based bioplastics can also be combined with natural textiles, fibres, and fillers to create polymer composites with enhanced mechanical strength and functional properties. These composites are particularly useful in the automotive, construction, and furniture industries, where they offer sustainable alternatives to conventional materials. The integration of algae biopolymers with natural fibres such as jute, hemp, or flax results in lightweight, durable, and eco-friendly materials with a wide range of industrial applications. This versatility highlights the transformative potential of algae-based bioplastics in promoting sustainable innovation across multiple sectors (Rajpoot et al., 2022).

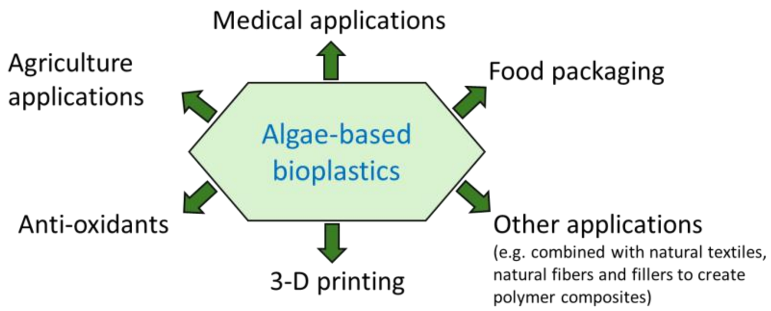


Figure 18: Key applications of algae-based bioplastics (Information from Rajpoot et al., 2022).

Biopolymer production from algae can be achieved through three main approaches, each offering unique processes and applications (Rajpoot et al., 2022) (Figure 19).

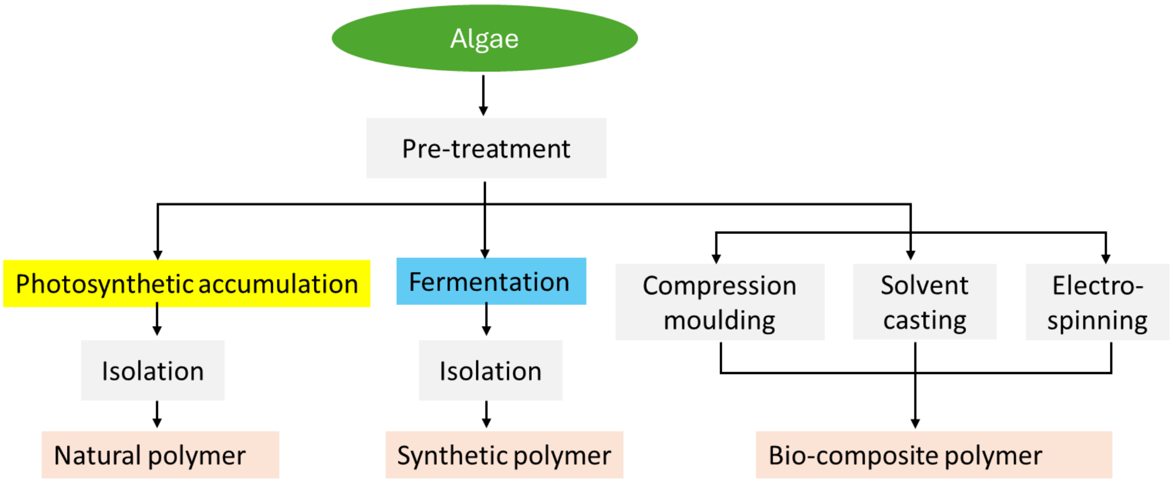


Figure 19: Various methods of producing polymers from microalgae (Modified from Rajpoot et al., 2022).

The first approach involves photosynthetic production, where microalgae synthesise biopolymers within their biomass during photosynthesis, utilising minimal nutrients (Costa et al., 2018). Light intensity and periodicity play a critical role in enhancing the accumulation of specific organic molecules, with adjustments in exposure time further boosting biopolymer formation (Cassuriaga et al., 2018). Emerging techniques, such as UV irradiation, have shown promise for eco-friendly synthesis by producing free radicals that crosslink starch molecules, resulting in biopolymers with tailored properties.

The second approach is fermentation-based conversion, where algal biomass is broken down and converted into bioproducts containing biopolymers (Khan et al., 2018). Enzymes produced by algae facilitate this process, and pre-treatment methods such as hydrothermal processes help extract essential carbohydrates, proteins, and lipids from the biomass. These components are then fermented to produce valuable biopolymers, such as polyhydroxyalkanoates (PHA), demonstrating the potential for scalable bioplastic production (Steinbruch et al., 2020).

The third approach focuses on algae-polymer blends, combining algae with other materials to create bio-composites. Techniques such as compression moulding and solvent casting are commonly used to produce films and other composite structures (Ciapponi et al., 2019). For instance, PVA-algae blends can be formed by air-drying mixed components to generate biopolymeric films. These blends are extensively studied for their mechanical, thermal, and biodegradable properties, making them suitable for diverse applications in sustainable materials (Sabathini et al., 2018). Together, these approaches highlight the versatility of algae as a feedstock for biopolymer production, offering innovative solutions for sustainable materials and advancing the field of bioplastics.

An example of using algae for wastewater treatment and bioplastic production was demonstrated by López Rocha et al. (2020). Their study highlights the potential of microalgae consortia for bioplastic production and nutrient recovery from a nitrogen- and phosphorus-containing treated wastewater effluent (obtained from a secondary sedimentation tank). The microalgae consortia was composed of *Scenedesmus obliquus* (50%) and *Desmodesmus communis* (30%) microalgal species, and cyanobacteria *Nannochloropsis gaditana* (10%) and *Arthrospira platensis* (10%). Initially, the consortium was employed to remove nitrogen and phosphorus from wastewater, demonstrating its capability for treating nutrient-rich effluents. The potential of the consortium, which exhibited a high protein content (~48%) for bioplastic production was then evaluated. A commercial *Arthrospira maxima* biomass, was used as a reference material for comparison (López Rocha et al., 2020). The bioplastic production involved blending the algal biomass with varying amounts of glycerol and forming bioplastic samples through injection molding. The resultant materials were characterised for their thermal, mechanical, and water-absorption properties using techniques such as dynamic mechanical thermal analysis (DMTA), water immersion tests, and tensile strength assessments (López Rocha et al., 2020). Their results demonstrated that all bioplastics exhibited a glass transition temperature of approximately 60°C, indicating thermoplastic behaviour. Interestingly, bioplastics derived from the wastewater-harvested biomass showed greater thermal resistance and lower water absorption capacity compared to those derived from *Arthrospira maxima* biomass (control). These properties were attributed to the reduced deformability observed in tensile tests, suggesting a more rigid structure in microalgae consortia-based bioplastics. Additionally, the mechanical properties, including strength and durability, improved as the biomass content in the bioplastics increased, regardless of the biomass type used (López Rocha et al., 2020). This example underscores the potential of algae cultivation as an approach to integrating wastewater treatment with bioplastic production. The ability to simultaneously remove pollutants from wastewater and create value-added bioplastics illustrates a promising approach to addressing both environmental and material sustainability challenges.

Nonetheless, while algae demonstrate significant potential as a sustainable resource for bioplastic production, the industrial-scale production of algae-based bioplastics has yet to be realised (Yap et al., 2023). The development of algae-based bioplastics is still in its early stages, with numerous factors requiring further exploration, including comprehensive techno-economic and life cycle assessment (LCA) studies to evaluate their environmental and economic impacts (Yap et al., 2023). The production costs of algae-based bioplastic films remain significantly higher than those of conventional synthetic plastics, posing a major challenge to their large-scale adoption and market competitiveness (Yap et al., 2023).

Looking forward, the development of strain- and application-specific, energy-efficient biomass harvesting methods is essential for the successful implementation of microalgal bioremediation in mine water treatment. In this context, self-settling strains or bioflocculating strain consortia offer significant potential to reduce energy consumption and operational costs (Al-Jabri et al., 2021). Continued advancements in algal biotechnology, combined with innovations in bioprocess engineering, are expected to address these challenges, positioning algae as a resource for sustainable bioplastics and integrated mine water treatment systems.

Algae-based biofuels

Growing algae in mine waters presents a promising and innovative approach to biofuel production while simultaneously addressing environmental concerns associated with mining activities. The nutrient-rich, often metal-laden effluents from mining operations provide an ideal growth medium for various microalgal species, which can thrive in these challenging conditions. Algal biomass supports a diverse range of biofuel options (Figure 20), making it a versatile resource for renewable energy production. The production pathways include various biochemical, bioelectrochemical, chemical or thermochemical pathways. Biochemical processes include fermentation of alcohols, anaerobic digestion to biogas and biological hydrogen production. Microbial fuel cells are a type of bioelectrochemical system that can convert organic carbon to bio-electricity. Chemical transesterification reactions can enable the production of biodiesel from algal lipids. Thermochemical processes include pyrolysis, gasification, liquefaction and combustion, which can generate syngas, biogas and charcoal, bio-oil or bio-electricity (Singh et al., 2023 Figure 20). The primary biofuel derived from algal biomass is biodiesel, produced through the transesterification of lipids, particularly triglycerides, which can constitute up to 60% of the dry weight in certain microalgal species like *Nannochloropsis* (Paramasivam et al., 2021). Additionally, algal biomass can be converted into bioethanol through fermentation processes, utilising the carbohydrates present, with some species (e.g., *Chlorella vulgaris*) showing carbohydrate content as high as 50% of their dry weight (Xu et al., 2011). Furthermore, the potential for producing biogas through anaerobic digestion of algal biomass offers another avenue for energy generation, with studies indicating that algal residues can yield biogas with methane content exceeding 60% (Solé-Bundó et al., 2019). Furthermore, through thermochemical conversion processes, algal biomass can be transformed into solid, liquid, and gaseous biofuels. For instance, torrefaction yields solid biofuels that can be used for heat and power generation, while liquefaction and pyrolysis primarily produce bio-oils, which can be further upgraded for chemical applications or used directly as fuels (Chen et al., 2015). Additionally, gasification generates synthesis gas, a versatile energy source that can be converted into liquid fuels.

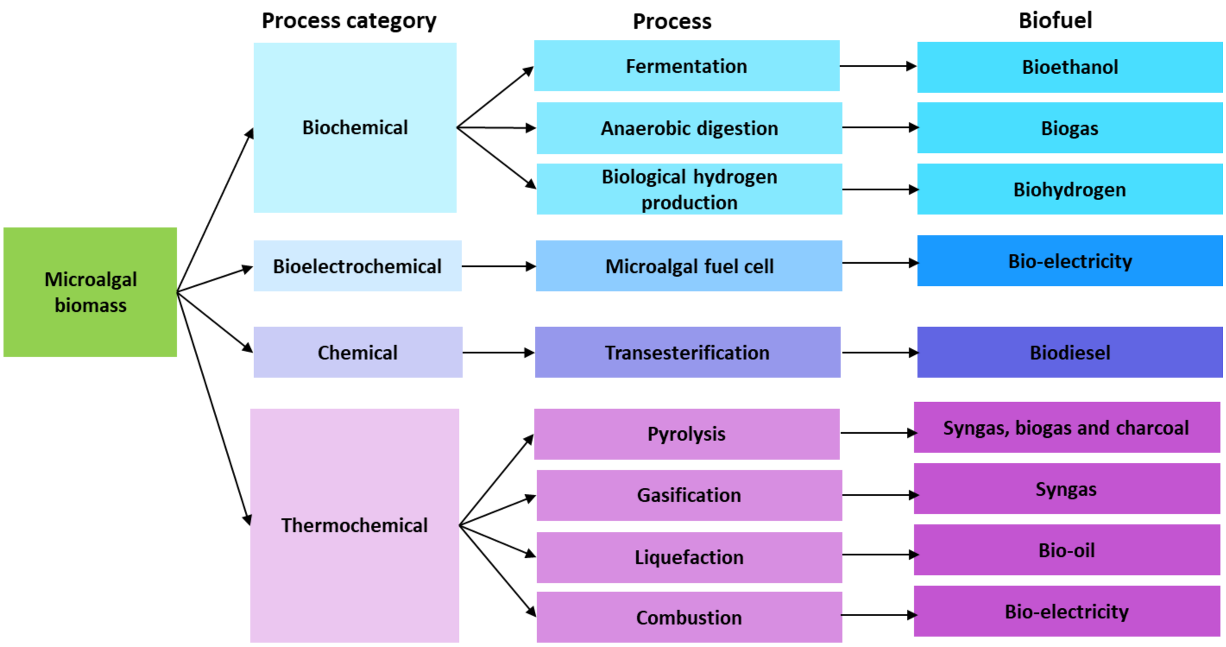


Figure 20: Biofuel options for algal biomass feedstocks (Adapted from Singh et al., 2023).

By cultivating endemic microalgae biofilms in phosphate-enriched tailings water, Palma et al. (2017) demonstrated a biomass productivity of 0.77 g (dry weight) $m^{-2}d^{-1}$, indicating the potential for high yields in challenging environments. The biomass produced contained a high carbohydrate content of up to 40%, which is advantageous for bioethanol production through fermentation processes. Additionally, the lipid content, while variable, reached 6.70% in the tailings water, suggesting potential for biodiesel extraction. The microalgae also demonstrated effective metal removal capabilities, with reductions of 24.8% for nickel and 26.3% for strontium, highlighting their role in bioremediation and enhancing the sustainability of mining operations. Overall, the process not only could facilitate the conversion of waste into valuable biofuels, such as biodiesel and bioethanol, but also can contribute to the bioremediation of contaminated waters by reducing heavy metal concentrations. This dual benefit enhances the sustainability of mining operations, turning waste management challenges into opportunities for renewable energy production, thereby promoting a circular economy in the resource extraction sector (Palma et al., 2017).

There are many abiotic stresses associated with mine waters, such as elevated salinity, extreme pH and heavy metal concentrations, and some microalgal strains are capable of thriving in these harsh conditions, enhancing lipid production—a critical component for biofuel production applications. Specifically, the stress responses of microalgae to these environmental factors appear to trigger metabolic pathways that prioritise lipid synthesis (Singh et al., 2023). For instance, nitrogen starvation has been shown to increase lipid accumulation in *Scenedesmus rubescens*, with lipid content rising to 38% of dry weight (Jo et al., 2020). The same organism showed an increase of carotenoid content of 6.94 mg L^{-1} once treated with light and salinity and in contrast the increase was only 1.75 mg L^{-1} under nitrogen deficiencies, 4.15 mg L^{-1} in salinity, and 1.32 mg L^{-1} in high light intensities. Under stressful pH conditions, microalgal strains such as *Scenedesmus* spp. Lig 290, isolated from a low pH waterbody (pH = 4.5) near an abandoned lignite mine, demonstrated robust growth and high lipid production rates (Eibl et al., 2014). Specifically, *Scenedesmus* spp. Lig 290 achieved a biomass productivity of approximately 52 mg $L^{-1}d^{-1}$ at pH 4 and maintained growth even at pH 3, showcasing its adaptability to harsh conditions. This adaptability not only enhanced lipid yields from 30-50% of dry cell weight under optimal stress conditions, but also reduces the risk of contamination from invasive species, a common challenge in traditional algal cultivation methods. Overall, these examples illustrate how abiotic stresses in mine waters can effectively enhance both biomass and lipid production, making microalgae a promising resource for biofuel production.

The co-production of valuable compounds, such as omega-3 fatty acids — specifically eicosapentaenoic acid (Callejón et al., 2022) and docosahexaenoic acid (Oliver et al., 2022) — alongside biofuels enhances the economic feasibility of algal biorefineries. For instance, *Nannochloropsis* can produce up to 20% of its biomass as omega-3 fatty acids (Paramasivam et al., 2021), underscoring the potential for algal resources to meet both energy and nutritional demands. This multifaceted approach not only addresses the growing demand for sustainable energy sources but also contributes to a circular bioeconomy by maximising the utilisation of algal resources.

Animal feed

Algae offer a sustainable and highly nutritious alternative to traditional animal-derived protein sources, especially as the global population is expected to reach 9.6 billion by 2050. For instance, microalgae species such as *Chlorella vulgaris* and *Arthospira platensis* have protein contents ranging from 40% to 60% of their dry weight, which is comparable to or even exceeds that of soy protein (Guccione et al., 2014). Additionally, microalgae can grow in marginal environments, utilising non-potable wastewaters such as mine waters and require minimal agricultural inputs, which makes them an eco-friendly option for protein production (Chisti, 2007).

Microalgae also exhibit high photosynthetic efficiency, converting approximately 6% of total incident solar radiation into biomass, significantly higher than terrestrial crops like sugar cane, which achieves only 3.5% to 4% (Kumar et al., 2022). Furthermore, they are rich in bioactive compounds, including antioxidants, essential fatty acids, vitamins and minerals. Algae can be utilised to produce several types of animal feed, benefiting from their high nutrient content, including proteins, carbohydrates, lipids, vitamins, and minerals. Examples of the types of animal feed that can be produced from algae include: livestock feed for poultry, pigs and cattle, aquaculture feed for fish and shellfish (Yarnold et al., 2019), petfood for cats and dogs, and speciality feeds for bees and other pollinator insects.

Incorporating algae into the diets of ruminants, such as cattle and sheep, can enhance their overall health and productivity, leading to improved milk and meat yields. Studies have shown that mixing small proportions of macroalgae with the feed of cattle can reduce methane emissions from their digestive activity by more than 95% (Fernández et al., 2023). In particular, Australian red seaweed (*Asparagopsis taxiformis* and *A. armata*) are known to decrease methane emissions in cattle and sheep when given as a dietary supplement (<1% of dry diet). The metabolites in the seaweed disrupts the enzymes responsible for CH_4 production in the rumen of these animals (CSIRO, 2024).

The inclusion of microalgae in livestock diets notably enhances growth performance by providing essential nutrients, improving feed conversion ratios, and enriching the fatty acid composition of meat (Madeira et al., 2017). Microalgae promote gut health and immune response, leading to better digestion and overall animal health. Their effects can vary by species, with successful incorporation into the diets of ruminants, pigs, poultry, and rabbits, making them a promising strategy for improving livestock productivity and meat quality.

Mine water can serve as a valuable resource for animal feed production through the cultivation of euglenoid organisms like *Euglena gracilis* (Krajcovic et al., 2015). These microalgae can thrive in harsh conditions characterised by low pH levels (approximately pH 3.0) and high concentrations of heavy metals, such as cadmium, chromium, and lead. This resilience allows them to grow in environments typically unsuitable for other organisms. For instance, *Euglena* can remove up to 98% of ammonium nitrogen, 93% of total nitrogen, 66% of phosphate, and 92% of organic carbon from domestic sewage within just a few days (Krajcovic et al., 2015).

By utilising mine water as a growth medium, *Euglena* has been demonstrated to produce biomass concentrations exceeding 20 g L^{-1} in batch cultures. This biomass is rich in nutritional content, making it a suitable feed supplement for animals. Specifically, when fed to shrimp, it has been shown to increase their tocopherol content (Krajcovic et al., 2015). This dual benefit not only aids in bioremediation efforts by purifying contaminated water but also provides a sustainable source of high-quality animal feed. Consequently, it contributes to more environmentally friendly practices in animal food production.

Several algal species have been commercially utilised as animal feed. *Arthrospira platensis* (formerly known as *Spirulina*) has an impressive protein content, which ranges from 46% to 63% (Rafiqul et al., 2005) and is a popular choice in aquaculture and livestock feed due to its rich nutrient profile. *Chlorella vulgaris* is recognised for its potential as a feed supplement, with protein content between 42% and 55% (Safafar et al., 2016), offering not only protein but also beneficial compounds that can enhance animal health. *Aphanizomenon flos-aquae*, another blue-green algae, is valued as an animal feed for its high protein levels of 60% to 75% of dry biomass weight. In addition to the above, other important microalgae include diatoms (Bacillariophyceae), golden algae (Chrysophyceae), and various species of green algae (Chlorophyceae) (Madeira et al., 2017). Notably, *Arthrospira*, *Chlorella*, *Dunaliella*, and *Haematococcus* are highlighted for their nutritional benefits in livestock diets. Heterotrophic marine organisms like *Crypthecodinium*, *Schizochytrium*, and *Ulkenia* are also cultivated for their high content of n-3 long-chain polyunsaturated fatty acids (n-3 LCPUFA), further enhancing the nutritional value of animal feed (Adarme-Vega et al., 2012).

In summary, the incorporation of algae into animal feed presents notable sustainability benefits, including resource efficiency by utilising non-arable land and minimising freshwater use, which alleviates pressure on traditional agricultural systems. Algae cultivation can reduce greenhouse gas emissions by absorbing carbon dioxide, while also recycling nutrients from waste products, thus mitigating pollution. This practice enhances agricultural biodiversity, contributing to ecosystem resilience and reducing reliance on monoculture feed crops. Additionally, algae serve as a sustainable source of n-3 long-chain polyunsaturated fatty acids, decreasing dependence on overfished marine resources. Overall, the use of algae in animal feed supports a circular economy by maximising resource efficiency and minimising waste, making it a promising strategy for sustainable livestock production.

Other bioproducts and applications

In addition to the previously mentioned applications of algae, there are also other innovative and specialised uses of algal bioproducts. The unique micro- to nano-scale naturally occurring components that make up their biology can provide useful materials. These include the calcium carbonate shell structures of Coccolithophores which can be used to produce biocement (Al-Mardeai et al., 2024), the macro-scale cellulose fibres which can be manufactured into nanocellulose (Ross et al., 2021) and bioactive compounds which may serve as naturally occurring pesticides (Silva et al., 2022). Some of the species which can be used for these types of bioproducts are shown in Table 12, along with notes regarding their growth conditions and processing requirements. As these are a new and emerging areas of technology very few Australian companies are involved in the manufacture and production of these bioproducts, however this is anticipated to be a high growth market.

Table 12: Compilation of other bioproducts obtained from various algae.

Bioproduct	Species	Notes	Growth conditions	Processing required	Reference
Plant growth stimulant	*Sargassum polycystum*	Widely used for plant propagation	Natural shallow seawater	Washing, drying, grinding, water mix, heat treatment, filtration of supernatant	Erulan et al., 2009
Algaecide, Herbicide and Insecticide	*Lyngbya* sp.	Over one hundred biologically active metabolites known	Collected from freshwater streams. Also some marine varieties of this genus.	Freeze-dried, ground ethanol extraction then ethanol evaporation to obtain aqueous extract	Berry et al., 2008; Silva et al., 2022
Insecticide	*Chlamydomonas reinhardtii* (combined with zinc oxide nanoparti-cles)	Double the insecticidal effect compared to nanoparticles alone	Tris–acetate-phosphate media	Algal extract from freeze-drying, heat treatment and sonication process	Rankic et al., 2021
Nanocellulose	Various e.g., *Oocystis apiculata* and *Nostoc muscorum*	Similar to plant cellulose but smaller fibre lengths	Various (depending on species)	Centrifugation, solvent and protease-lipase digestion	Ross et al., 2021
Biocement	*Chrysotila carterae*	Biocement proposed due to $CaCO_3$ produced by algae	Laboratory growth using modified seawater-based f/2 medium	Centrifugation and drying	Al-Mardeai et al., 2024
Biotemplates to improve lithium ion batteries	*Spirogyra* (Combined with Manganese(II) oxide nanoparticles)	MnO / Carbon composite to provide anode	Bold Basal Medium	Freeze-dried then chemical processing	Wang et al., 2016; Munir et al., 2015
Bioink for 3D printing	Various e.g., *Laminaria saccharina* and *Porphyra umbilicalis*	Polymers such as agar, alginate and carrageenan	Various (depending on species)	Extraction using heat treatment, water and solvents	Xu et al., 2017; Mandal et al., 2023

3. Opportunities and constraints

3.1 Mine water treatment technologies or amendments that may be required to make mine water quality amenable for algal growth

Large-scale microalgae ponds also require significant water resources. For example, 25 ha of open raceway tracks operating at a conventional depth of approximately 0.20 m (Roles et al., 2021) would require at least 50 ML of mine water to fill (Levett et al., 2023). The feasibility of cultivating algae in mine water largely depends on the quality of the water and the algae species selected. While the ideal scenario would involve no pre-treatment (minimising costs), in many cases, pre-treatment may be necessary to enhance algae yields and ensure the technical and economic viability of the process. Pre-treatment is particularly important when contaminants in mine water hinder algae growth. Mining operations often generate water with elevated concentrations of various contaminants, including excess acidity/alkalinity, metals/metalloids, suspended solids and salinity. Examples of potential contaminants or water quality parameters and their impacts on algal growth, and pre-treatment methods available to address these are shown in Figure 21. Mine water treatment technologies can be categorised as passive or active. Typical passive treatment technologies include limestone drains/channels and engineered wetlands. Examples of active treatment technologies include chemical precipitation, coagulation, ion exchange, and membrane separation technologies.

At some mine sites mine water pH may need to be increased or decreased to make it suitable to support microalgae growth, although the photosynthetic activity of algae increases pH, and several types of microalgae have been detected even in acidic mine water (Figure 6) (Levett et al, 2023). The management of mine-influenced water is critical to ensure not all mine water is mixed to become acidic (pH < 6). In contrast, for mines with only small acidic water volumes, the acidic water may be directly added to the microalgae growth system to reduce and control the pH, with no passive water treatment required. The optimum pH of the microalgae growth system is specific for the type of algae grown. Depending on the mine water pH and the target algae, lime or other alkaline substances can be used to neutralise acidic water. Lime treatment also removes some sulfate as gypsum. Conversely, acidic substances may be used to neutralise highly alkaline water from e.g., bauxite processing.

As discussed in section 2.4.2, several types of algae can facilitate the removal of metals from mine water. However, at some mine sites elevated metal concentrations may inhibit algal growth either directly through acute toxicity or indirectly through the formation of metal precipitates that reduce light penetration through the water. Pre-treatment options for removing metals include precipitation and coagulation using chemical or biogenic agents, ion exchange, adsorption and membrane capacitive deionisation. Moreover, algal biomass can be used as a substrate for biological sulfate reduction-based metal sulfide precipitation. Biological sulfate reduction can be implemented in passive constructed wetlands or active bioreactors. Constructed wetlands combine naturally-occurring biogeochemical, geochemical, and physical processes to remove various contaminants from mine waters, such as nutrients, sulfate and heavy metals as well as neutralise pH. This pre-treatment creates a more conducive environment for algae growth, where the algae in turn can further improve water quality by absorbing residual contaminants. Metal precipitates and other suspended solids can also be separated from water by filtration or sedimentation.

	Description of water characteristics	Inhibiting properties	Pre-treatment options
pH	Many mine waters are **highly acidic** due to the presence of sulfuric acid from sulfide mineral oxidation, whereas water from bauxite processing may be highly **alkaline**.	Although specific algae can grow in alkaline or acidic environments, these strains might not have the **required characteristics** for the intended application (e.g., heavy metal adsorption, specific product production).	**Lime** or other **alkaline substances** can be added to neutralise the acidity, making the water more conducive to algae growth. Alternatively, acidic substances may be used to neutralise alkaline mine water.
Metals	Many mine waters contain elevated levels of metals.	The **tolerance** of algae to heavy metals varies depending on the specific algal species, environmental conditions, and the form of the metal. In some cases, it might be necessary to **decrease the metal concentration** to allow for algae growth.	**Precipitation and coagulation** using chemical or biogenic agents, **ion exchange, adsorption and membrane capacitive deionisation** can be used to effectively remove heavy metals prior to algae cultivation.
Suspended solids	Mine waters can contain a variety of **sediments**, such as minerals, organic matter and other precipitates.	Suspended solids in mine water can **hinder light penetration** and algal photosynthesis.	**Filtration or sedimentation** processes can be used to remove these particulates, improving water clarity and promoting healthier algae growth.
Sulfate	Mine waters can range in **sulfate** concentrations with high concentrations often in acidic mine drainage.	Depending on the strain, mine water sulfate concentrations could be inhibiting growth.	**Lime treatment** removes sulfate as gypsum. **Biological sulfate reduction-**based passive or active processes facilitate effective sulfate removal and enable reagent (dissolved sulfide) generation for metal removal.
Salinity	Mine waters can range in salinity from fresh to highly saline.	Different algae thrive at different salinities. Depending on the strain, mine water salinities could be inhibiting growth.	**Reverse osmosis or novel membrane technologies** can decrease the salinity of the mine water prior to algae cultivation (although it would be recommended to chose algae which can tolerate the mine water directly to reduce costs).
Lack of nutrients	Typical levels of **nitrogen** and **phosphate**, as well as their forms, can vary widely across different mine waters.	Algae require nutrients such as nitrogen, phosphorus, and trace elements to thrive, and nutrient deficient waters would inhibit high **productivities**.	Mine waters could be **enriched** with fertilisers or nutrient-rich waste streams (e.g., agricultural runoff or other wastewaters) to support algal growth.

Figure 21: Overview of water characteristics influencing algal growth and technologies which can be applied for pre-treatment of mine water.

Nutrient levels in mine water can vary depending on the mineralogy of the ore and the possible use of explosives that contain ammonia and/or nitrate. If mine water nutrient content is low, fertilisers or nutrient-rich waste streams, such as agricultural runoff or aquaculture wastewater can be added to mine water to support algal growth.

Treatment technology selection and configurations are site specific and based on local conditions which can vary even when extracting the same product. Conditions include the chemical composition of the mine rock and subsequent wastewater (both of which can vary in quality over the mine's life), available space, and/or the quantity of water being treated. Key considerations to address site-specific treatment need to include the often-remote locations of mines and the corresponding impact on chemical supply chains, high energy load requirements, and needs for frequent maintenance.

3.2 Potential complementarity of algal production alongside other water uses

In the mining industry, water is essential not only for mineral production but also for activities such as controlling dust on surface mine roads. Many of the world's major mining sites are located in water-scarce areas. Northey et al. (2013) examined the water intensity of various open-pit copper mining operations across different countries. They found a wide range of water use, from 9.8 cubic meters per ton of copper to 350 cubic meters per ton, with an average of 70.4 cubic meters per ton. The key factors influencing water intensity included the aridity of the mining location and economies of scale, i.e. operations in arid regions use more water, whereas larger operations use less water per ton of copper produced (Northey et al., 2013).

Water reuse in operations may require treatment because of the effects of water chemistry on flotation, for example build-up of salt. Mine water can also be used potentially outside the mine for various purposes, but there are technical, economic, and environmental considerations including stringent water quality and quantity requirements for potential end users, treatment cost and complexity, and the availability of traditional water sources, such as surface and groundwater, which might present a less expensive water supply. Geographic distribution and variation in the mining industry are also other localised considerations for mine water reuse. Despite that, in water-scarce environments mine water use presents an opportunity. This is particularly important for prolonged drought periods caused by climate change in parts of Australia. There is also an opportunity to use mine water for irrigation of degraded landscapes outside the mining lease, e.g., for crop production. For example, in north Queensland there is an opportunity to use mine water for Pongamia tree plantations to produce biofuel. Rio Tinto is developing Pongamia seed farms in Australia as part of a new biofuels pilot, which aims to determine if Pongamia seed oil can contribute to Rio Tinto's renewable diesel needs while potentially contributing to the growth of a new biofuel sector in Australia. Algae-based technologies can improve the quality of water needed for crop irrigation, by removing contaminants, and also potentially provide the biomass and nutrients needed for establishing crops in low productivity soils.

Algae as a feedstock for biochar can be cultivated on non-arable land using wastewater from mining and mineral processing. While the biomass cultivated in mine wastewater can be enriched in some metals, slow pyrolysis of this high-ash biomass immobilises the metals in a biochar which can then be applied to soils to improve the yield of crops with no transfer of potentially toxic elements to either soil pore water or plants grown in the biochar soil mixtures in the short-term (Roberts et al., 2015a). Roberts et al. (2015a) showed that while the biomass produced from algae had relatively high concentrations of some metals, due to its cultivation in wastewater, the resulting biochar did not leach metals into the pore water of soil-biochar mixtures. The biochar did, however, contribute essential elements (particularly K) to soil pore water. The biochar had very strong positive effects on the establishment and growth of a native plant (Kangaroo grass, *Themeda australis*). They demonstrated that algal biochar can be produced from biomass cultivated in wastewater and used at low application rates to improve the rehabilitation of a variety of soils typical of coal mines (Roberts et al., 2015a).

The water stored in onsite reservoirs such as pit lakes, depending on their water quality, could be used as a potential water source for post mining land uses (PMLUs) such as irrigation of crops, stock watering, supporting the production of pumped storage hydropower, aquaculture, or development of recreational areas. There are other applications of pit lakes, for example aquaculture, as summarised by McCullough et al. (2020) (Figure 22). Algae-based technologies can benefit aquaculture by 1) providing biomass for aquaculture feed, 2) improving water quality, 3) probiotic effects of microalgae in aquaculture systems, 4) improving microbial community in water environments, 5) and aquaculture effluent remediation. For example, near Collie in WA, treated water from an old coal mine has been used at a commercial Ngalang Boodja marron farm. The farm has generated work for Aboriginal community (Fitzgerald, 2014) and serves as a precedent for how mine water has been used to create sustainable economic opportunities in a post-mining landscape.

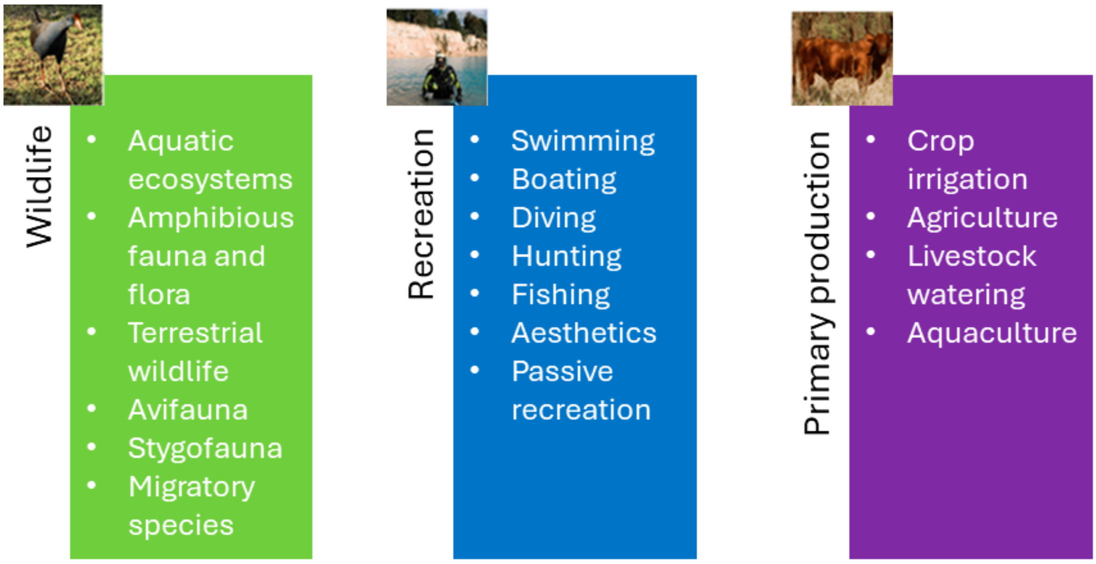


Figure 22: Various uses of pit lakes (Reused from McCullough et al., 2020 with Creative Commons Attribution (CC BY) license http://creativecommons.org/licenses/by/4.0/).

Algae-based technologies can be part of a hybrid bioremediation process that relies on the use of microorganisms, microalgae (bioadsorption, biological sulfate reduction), and the use of plants (phytoremediation) for the removal of contaminants from mine water. For example, halophytes have been explored for their potential to address issues related to saline-affected soils and water, through desalination processes. Phytodesalination is a sustainable approach that utilises halophytes to remove salt through the mechanism of salt accumulation or salt extraction, primarily sodium and chloride ions, in plant tissues from saline soils or waters. These plants can uptake and accumulate salt in their tissues, and they can be used for soil reclamation and to reduce salinity levels in areas affected by salt-affected soils or brackish water (Shaygan et al., 2018).

Based on a recent Australian Coal Industry's Research Program (ACARP) study (Lund and Blanchette, 2021) one main limitation to rehabilitating the pit lakes is related to the creation of littoral and riparian areas and developing strategies to enhance natural ecological successional processes. Microalgae, in particular, play a crucial role in enhancing the productivity, biodiversity, and functioning of aquatic ecosystems. Algae-based technologies can be potentially combined with phytoremediation techniques to improve the biodiversity of the pit lakes by developing appropriate riparian and aquatic planting.

Figure 23 shows examples of embedding algae-based technologies during the operational phase of a mining project and after closure, including CO_2 capture, treatment of mine water from seepage collection dams, tailings and open pits, mine waste stabilisation, dust suppression, mine site rehabilitation, and the production of various algae-based products such as fertilisers and biostimulants, animal feeds, biofuels, pigments and bioplastics.

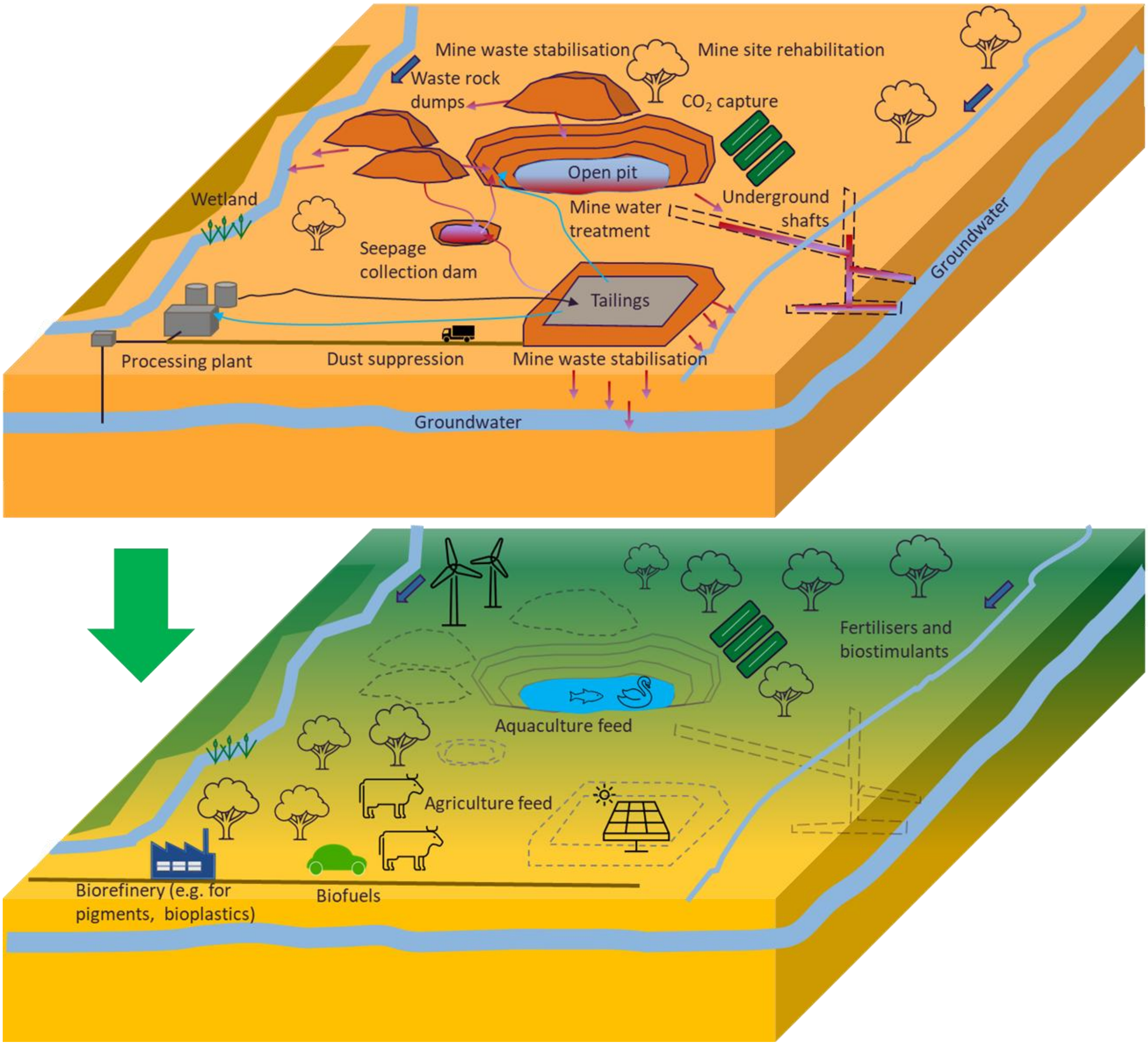


Figure 23: Embedding algae-based applications to mine sites during the operational phase of mining and after mine closure.

3.3 Potential for dual objectives to be compatible

The underestimation of costs and time of mine closure are major drivers for the poor track record of mine closures (Measham et al., 2024), and many examples of mining companies being unable to meet their closure obligations. Residual risk or liability is an important aspect of relinquishment, representing the risk or liability that remains after all closure activities have been completed (Measham et al., 2024). Concerns about residual risk inhibit relinquishment of mine leases, which transfers liability of the site. Thousands of mines are in 'care and maintenance' partly because of the difficulties involved in closing a mine and concerns about transfer of residual liability for sites (Measham et al., 2024). Post mining land uses include agriculture, forestry, lake or pool, intensive recreation, non-intensive recreation, construction, and conservation, pit-backfilling (Measham et al., 2024). Repurposing of mined land has increasingly been seen as an important closure opportunity (Maybee et al., 2024). Repurposing opportunities are diverse, offer the possibility of generating post-mining value and business opportunities using new and innovative technologies and solutions (Perlatti and Gagen, 2024). In the context of "economic rehabilitation", mined land can be used for the production of low value algae products that benefit from large scale production. Microalgae have shown significant potential in the production of various bioproducts, for a wide range of applications, including biofuels, chemicals, food, feed, and pigments (Reisoglu and Aydin, 2023). The advantages of microalgae include their high productivity, the ability to cultivate them on marginal land using fresh or saltwater, which minimises competition with food crops, and the potential to integrate biomass growth with the treatment of waste streams.

Cultivation of microalgae for applications such as fuel, food, pharmaceuticals and farming is a rapidly developing area of research and investment. Also, the capacity of microalgae for biomonitoring enables effective assessment of water pollution levels after mine closure. There is a strong interest in how microalgae can contribute to soil rejuvenation, carbon credits, and biomass management. The carbon capture potential of microalgae is a major incentive for many mining companies. The process of carbon fixation by microalgae holds great potential for sequestering CO_2 from the atmosphere, offering possibilities for sustainable utilisation such as bioenergy production and the development of value-added products (Figure 24). When microalgae biomass is used to produce biofertiliser, biostimulants and/or biochar for mined land rehabilitation, there may be potential to increase the total carbon sequestered by accelerating both soil carbon sequestration and plant biomass production (Antonelli et al., 2018).

One potential dual-purpose system is microalgae–bacteria-based systems for treating wastewater and production of biofuels and chemical products, with substantial savings in the overall cost of microalgae biomass production. The costs of algal production and harvesting using wastewater treatment can be covered by the wastewater treatment plant (Park et al., 2011). This integrated approach not only addresses wastewater management but also presents an opportunity for resource recovery and the production of valuable products. Also, the remote nature of many mines worldwide restricts the widespread use of biowastes in mine rehabilitation due to high transport costs for low-value, high-tonnage materials. Using mining influenced waters to produce microalgae, a renewable bioavailable carbon source, onsite would reduce the transport burden and contribute to the goal of improving mine site rehabilitation outcomes using carbon neutral/negative technologies. Using microalgae to produce biodiesel has several advantages for producing renewable energy, including being one of the very few biofuels with negative CO_2 emissions (-183 kg CO_2 MJ^{-1}) (Chisti, 2007; Christi, 2008). Whilst microalgae promises to deliver many environmental benefits compared with existing biofuel technologies, there are also issues to overcome in relation to wastewater management, emissions control, land use change and responsible development of genetically modified organisms.

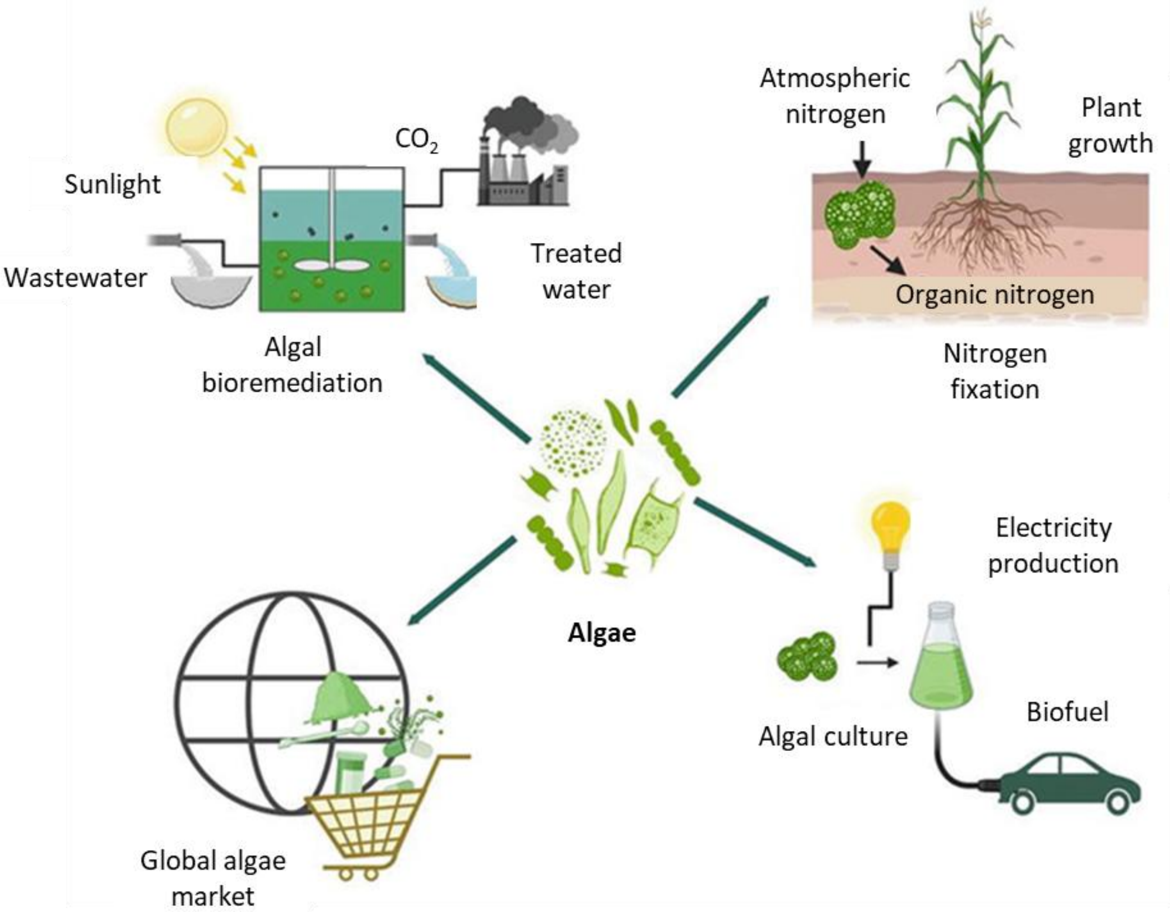


Figure 24: Algal technologies and land rehabilitation (Reused from Reisoglu and Aydin, 2023 with Creative Commons Attribution 3.0 License).

3.4 Opportunities to engage local communities in algal biotechnology-based economic transitions for mine site closure

The closure of mines presents unique opportunities for the creation of secondary economies. By leveraging existing infrastructure, technological expertise, and local resources, one can foster innovation and diversify economic activities. Renewable energy projects, eco-tourism, agriculture, and manufacturing are just a few examples of sectors that can flourish in post-mining communities.

However, there are few examples of successful post-mining transition to learn from. A recognised issue is failure to undertake inclusive stakeholder engagement (Measham et al., 2024). The terms public participation, consultation and engagement are often used interchangeably. Consultation is a process led by a proponent (e.g., industry or government) with a particular goal, such as a project that needs to be discussed. Public participation is the involvement of those affected by a decision in the decision-making process. Engagement is the process of building ongoing relationships and trust with communities. In the context of mining, engagement may start in the earliest stages of exploration or project development, extending throughout the mine life. Therefore, consultation and public participation are about specific projects or interventions, whereas engagement is about an ongoing relationship with impacted people.

Keenan and Holcombe (2021) reviewed cases of repurposing mines globally and identified stakeholder and community engagement practices as an important factor that influence whether repurposing occurs.

Whether the company has a ‘beyond the gate’ approach to local/regional stakeholder engagement and has policies and procedures to ensure that they look beyond the purely operational and technical factors that occur within the mining lease to the social impacts of the operation. An inclusive approach to community engagement through life of mine, including during concurrent or progressive reclamation, will more likely lead to positive post-mining land-use transitions (Keenan and Holcombe, 2021).

A collaboration framework recently developed for post-mining land use opportunities (Worden et al, 2024) could be used for algae-based technologies (Figure 25). Worden et al. (2024) showed the potential for effective collaboration is linked to a specific PMLU (or an integrated system of different PMLUs) and that options are driven by a mine location’s socio-economic, environmental and regulatory context.

Figure 25: A collaboration framework that can be used for the algal biotechnology implementation. PMLU = post-mining land use (reused from Worden et al., 2024 with Creative Commons license 4.0).

Step 1 assumes that a broad group of regional stakeholders has come together to explore a PMLU option and its collaborative potential. Step 2 establishes the terms of reference for the PMLU project (collaboration process). In other words, regional stakeholders should use the knowledge and understanding of available assets as the basis for the collaboration. Assets include the skills, expertise, local and/or First Nations knowledge, and available financial and human resources. Step 3 is about adhering to the collaboration principles such as trust, mutual respect and complementarity of resources provided by all collaborators (Siemon et al., 2019). Step 4 is about assessing the PMLU suitability, which relates to the environmental, socio-economic, policy and global context.

Some of the benefits of algae-based technologies for the communities include:

Develop enterprises and suppliers: Mining companies can develop partnerships with local entrepreneurs and small businesses. By nurturing local enterprises, mining industry can unlock economic potential, create jobs, and cultivate a sustainable ecosystem that extends beyond mining.

Foster skills development: Investing in education and skills training is essential for empowering local communities. Training programs, apprenticeships, and educational initiatives equip individuals with diverse skill sets, enabling them to participate in emerging sectors and fill job market gaps.

Promote local procurement: By prioritising local procurement, the technology will contribute to the growth of nearby businesses and industries. This approach bolsters the resilience of local economies, enhances supply chain efficiency, and establishes a foundation for post-mining success.

Facilitate collaboration: Collaboration between mining companies, government agencies, civil society organisations, and local communities is crucial. Establishing platforms for open dialogue, sharing best practices, and creating synergies will accelerate the transformation of mining communities and unlock untapped opportunities.

Strategise for mine closure: Recognising that mine closures are inevitable, proactive planning is essential. Mining companies will engage with local stakeholders to develop comprehensive closure plans that emphasise sustainable land rehabilitation, job transition programs, and the repurposing of mining infrastructure for alternative industries.

3.5 Strategy for the engagement with Traditional Owners

Traditional Owners have Traditional Ecological Knowledge on various algal applications that can potentially be brought together with Western science to add new understanding. As part of this Stage 1 project, Regional Economic Solutions Pty Ltd (RES) was engaged to develop a Traditional Owners engagement strategy that would establish the basic parameters for this type of engagement and how it could be consistently applied across a range of sites and projects identified under the CRCTiME project. As the cultural knowledge, techniques and processes employed by RES to deliver the strategy remain the intellectual property of RES, the strategy is documented in a separate report to be shared with CRC TiME team within the CRC TiME project 3.15 Algae-based technologies for improved environmental outcomes and sustainable post-mining futures.

3.6 Regulatory or other constraints that may limit growing and utilisation of algal biomass for specific applications

Regulatory requirements are crucial considerations within the context of cultivating and applying algae at mine sites, as they ensure that algae cultivation at mining sites complies with environmental, safety, and operational standards. For example, in Western Australia, activities at operational mine sites are currently regulated under Part V of the Environmental Protection Act 1986 (the EP Act) (Government of Western Australia, 1986). Licences issued under Part V of the EP Act typically include conditions to ensure that emissions to land air or water do not pose an unacceptable risk to human health or the environment. Therefore, the mechanisms applied within licences to regulate cultivating and harvesting algae at mine sites would depend on the nature of any emissions to land air or water associated with the activity. The nature of such emissions might vary greatly depending on how the harvested algae is proposed to be used – i.e., whether it is applied to land for rehabilitation purposes or used externally to the mine site activities. Furthermore, any works required to support cultivation and harvesting of algae (such as construction of ponds) would require a works approval, and subsequent operation would likely require a licence amendment to ensure that appropriate maintenance, monitoring and reporting conditions were in place to minimise any risks associated with the process (Personal communication, 2024). Some regulations may have a positive impact in helping to mitigate potential risks associated with the use of algae in sensitive environments, such as the release of non-native species, the management of heavy metals, and the discharge of treated water. Other regulations, however, may impede the deployment of algae-based commercial activities on mine sites and should be carefully navigated to ensure beneficial environmental impacts. Figure 26 indicates some anticipated regulatory requirements which would be applicable within the current context.

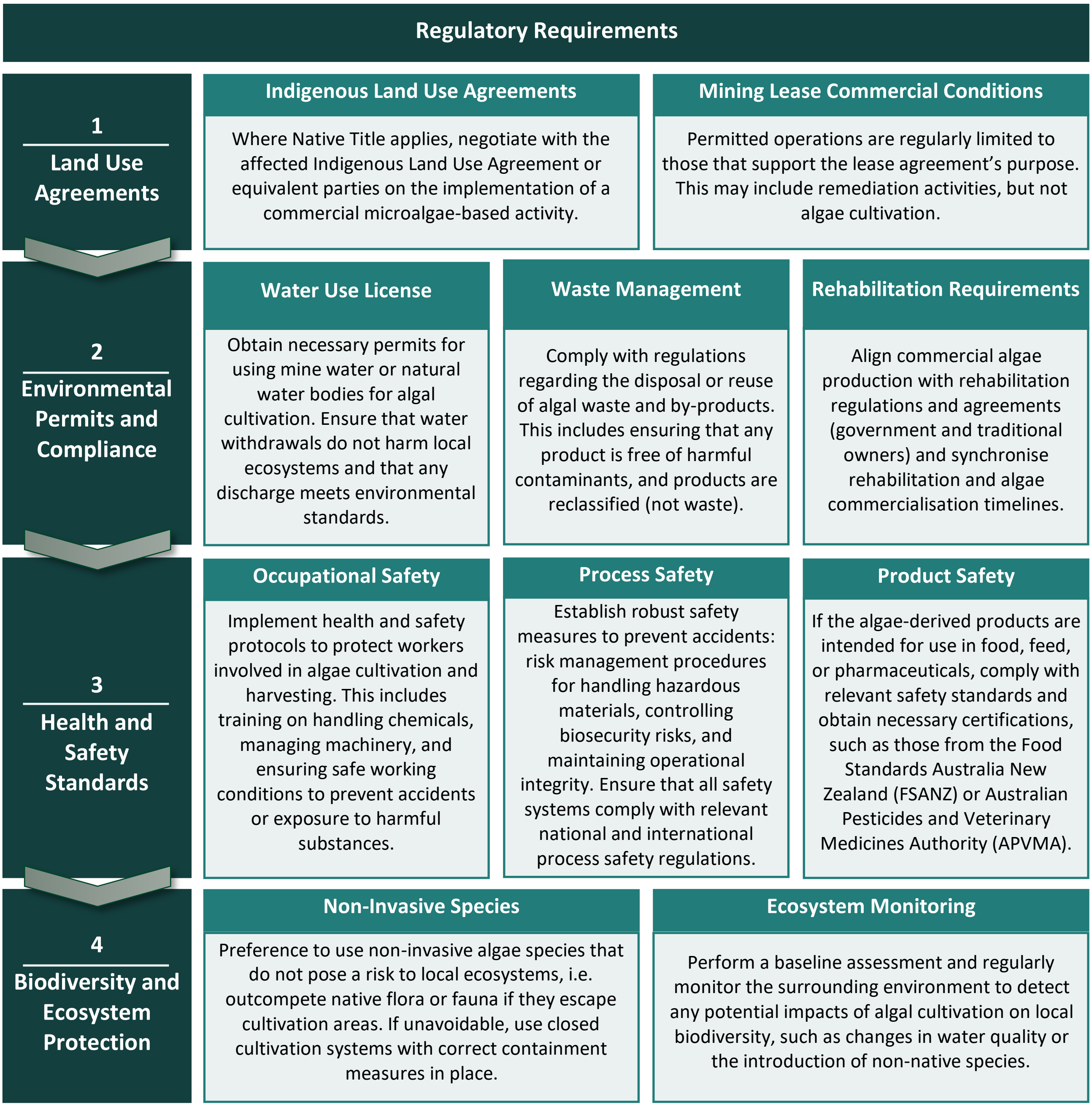


Figure 26: Anticipated regulatory requirements for cultivation of algae within mining contexts.

Due to the innovative nature of the concept however, relevant regulations might not be in place yet, or it might be unclear which regulations are applicable. For example, a legislated recovered materials framework is currently under development in Western Australia to provide a mechanism to authorise the manufacture and use of recovered/waste-derived materials. While the detail of the proposed framework is currently unclear, it is possible that re-use of algal biomass products for off-site applications could be managed within the framework (Personal communication, 2024). In another example applicable for the Northern Territory (NT), algal biomass is not specified in Schedule 2 of the *Waste Management and Pollution Control (WMPC) Regulations 1998* (Northern Territory of Australia, Department of Lands, Planning and Environment, 1998), which prescribes wastes for the purposes of the definition of a listed waste. As such, an authorisation would not be required under the WMPC Act 1998 to store or dispose of algal biomass on land. However, if there are listed wastes combined with the algal biomass, a licence would be required. Moreover, it is unclear if the algal biomass would be considered a biosolid, and biosolid guidelines for the NT are still forthcoming (Personal communication, 2024). For this reason, it will be crucial in following stages to determine all applicable regulatory factors, as well as to engage with government and environmental organisations to ensure long-term viability and acceptance of algae-based technologies in the mining industry.

Furthermore, there could also be potential cultural constraints or barriers which will need to be navigated. These will be heavily site specific, depending for example on existing agreements with Traditional Owners or rehabilitation timeframe agreements with authorities. For certain mine sites such agreements can state that mining companies are responsible for mine-site rehabilitation and to what degree, i.e. ensuring that there will be no unnatural landforms or batters post mining. For instance, if the mining voids of a mine site have water stored in them, an agreement would be needed with any affected traditional owners to allow for retention of the voids for algae cultivation. It will be critical to align the timelines and objectives of site rehabilitation with the commercialisation of algae, as rehabilitation projects typically follow strict timelines and monitoring to meet environmental standards. Commercial algae cultivation, which may require time to scale up, must operate within these established rehabilitation schedules to ensure compliance and harmony between environmental recovery and commercial goals.

3.6.1 Queensland case study: algae-based technology deployment on coal mining sites

The following attempts to sketch out regulatory requirements that may impact on the commercial viability of delivering microalgae-based solutions on a Queensland mining lease area. The case study makes two primary assumptions:

- The commercial operation will be deployed on a coal mining site.
- The commercial operation will occur on an active mining lease area. This seems like a reasonable assumption considering that it will likely take more than 10 years for a Queensland coal mine to relinquish its mining lease.

1. Land Use Agreements

Mining lease commercial conditions and constraints

Queensland's *Mineral Resources Act 1989* (Queensland Government, 1989) does not provide for the undertaking of commercial activities other than those that support the purpose for which a mining lease was granted. For example, a mining lease is subject to the condition that the holder shall use the area of the mining lease bona fide for the purpose for which the mining lease was granted and in accordance with this Act and the conditions of the mining lease and for no other purpose (Section 276, 1A).

As such, it remains unclear if an entity can generate revenue from an algae-based business activity on an active mining lease. The Act does, however, make provision for remediation activities which it defines, among other things (Section 344A) as:

(f) mitigating, managing, treating or cleaning up pollution that is on an abandoned mine site or affected land because of, directly or indirectly, previous mining activities

(k) assessing the commercial or practical feasibility of an abandoned mine site for the future exploration and mining of minerals or another use.

Legal advice is required to determine if a remediation activity can operate as a commercial entity that generates revenue from the sale of harvested biomass.

Indigenous Land Use Agreements (Native Title implications)

Some Queensland mining lease areas are subject to Native Title under the *Native Title Act 1993* (Australian Government, 1993). Where this is the case, the mining lease holder will have entered into an Indigenous

Land Use Agreement (*Native Title Act (Queensland)]* (Queensland Government, 1993)). The implementation of a commercial algae operation within the mining lease area will require consultation to occur between the Indigenous Land Use Agreement parties. This consultation could result in an agreement to provide financial compensation for carrying out the commercial activity on this land.

Native Title will also have potential financial implications if an enterprise undertakes to register its activities as an Australian Carbon Credit Unit (ACCU) Scheme project. On land where Native Title applies the *Carbon Credits (Carbon Farming Initiative) Act 2011* (Australian Government, 2011) requires a project proponent to obtain the consent of the registered Native Title body corporate to an application for a declaration of a project as an eligible offsets project.

2. Environmental permits and compliance

The primary environmental regulatory challenges for the cultivation and use of microalgae on mine sites in Queensland relate to the use of mine-affected water and waste implications.

The use of mine-affected water for microalgae cultivation

Within Queensland, the conditions that regulate the undertaking of environmentally relevant activities within a mining operation are set out within a mine site's Environmental Authority (EA) granted under the *Environmental Protection Act 1994* (Queensland Government, 1994). The EA makes provisions for the mining lease holder to take mine-affected water for supporting activities permitted within an EA. If an algae-based operation is permitted under the *Mineral Resources Act 1999*, it will presumably have the right to take water for this purpose without requiring any additional water license that would apply to non-mining operations.

Since 2019 the holders of EAs related to mining activities are required to receive approval of a Progressive Rehabilitation and Closure Plan (PRCP) that outlines how they will undertake progressive rehabilitation of the land disturbed by mining activities (authorised under the EA) back to a stable condition (Queensland Government, 2024). For algae-based activities that an entity intends to continue after mine closure, it will be necessary for these to be approved within the site's PRCP.

Waste recycling legislation implications

Within Australia, a State Government must approve the conditions under which a mining operation undertakes environmentally relevant activities. For example, in Queensland the *Environmental Protection Act 1994* (Queensland Government, 1994) provides for the granting of an Environment Authority (EA) that sets the conditions for undertaking mining activities. The EA serves as the regulation to which a mine site must adhere to for the discharge of mine-affected water. Each mine site's EA provides specific guidelines that prescribe release points, water monitoring requirements and water contaminant trigger levels that may prevent discharge depending on natural water way flow rates. Equivalent site-specific regulatory mechanisms apply to mining leases in NSW (*Environmental Protection License*), Western Australia (*Mine Closure Plan*) and the Northern Territory (*Environmental [Mining] License*).

Queensland makes a provision for the controlled use of mine-affected water off a mining lease area. Most Resource EAs contain the following generic text (Department of Environment, Science and Innovation, 2024a):

> *Mine-affected water may be piped or trucked or transferred by some other means that does not contravene the conditions of this environmental authority and deposited into artificial water storage structures, such as farm dams or tanks, or used directly at properties owned by the environmental authority holder or a third party (with the consent of the third party).*

This provision may provide scope for re-purposing mine-affected water to cultivate microalgae off a mining lease, thereby avoiding the onerous conditions of operating under the Coal Mining Health and Safety Act

1999 (Queensland Government, 1999). The other states do not appear to make an allowance for using mine-affected water offsite within their environmental approval process.

Though resource EAs permit the taking of void water for mine related activities, its status as a “waste” under section 13 of the *Environmental Protection Act 1994* (Queensland Government, 1994) will require an End of Waste Code (EOWC) to recognise its use as a resource and to prescribe any requirements and/or conditions for its use as a resource as required by section 159 of the *Waste Reduction and Recycling Act 2011* (Queensland Government, 2011). An EOWC is already in place for the use of underground water “taken or interfered with” (defined as “associated water”) while undertaking authorised activities within a mining lease (*EOWC: Irrigation of Associated Water (including* coal seam gas *water)* (ENEW07546918) (Department of Environment, Science and Innovation, 2024c); compare section 334ZP of the *Mineral Resources Act 1989* (Queensland Government, 1989)). The objective of the *EOWC: Irrigation of Associated Water* is to encourage the beneficial use of coal seam gas water in a way that protects the environment and maximises its productive use as a valuable resource.

Depending on how the produced algal biomass is processed, salts and possibly water from mine voids may remain in final products transported offsite. These will need to be accounted for within a specific EOWC. The latter will likely be comparable to the EOWC *End of Waste Code Water Treatment Residuals* (ENEW07503318) already in place for recognising water treatment residuals as a saleable resource (Department of Environment, Science and Innovation, 2024b).

Additional regulatory frameworks govern the production and reprocessing of waste. *The Environmental Protection Regulation 2019 – Schedule 2* (Queensland Government, 2019) specify prescribed environmentally relevant activities (ERAs). Should the processing of harvested biomass produce brine waste, this outcome will trigger Model operating conditions ERA 60 – waste disposal (Department of Environment and Science, 2017). The downstream use of biomass produced from integrating nutrient waste streams may trigger ERA 55 – Other waste processing or treatment, which covers waste recycling or reprocessing (Queensland Government, 2019). This may apply, for example, if an aquacultural facility receives biomass produced from the cultivation of algae using waste N and mine-affected water (Environmental Protection (Waste ERA Framework) Regulation 2018 (Queensland Government, 2018)).

Once the legislated environmental implications for recycling waste are addressed, the processing of algae biomass into products for human and animal consumption will need to comply with the same regulatory standards that apply outside a mining-related context: For example:

- **Human food:** The *Australian New Zealand Food Standards Code* (Food Standards Australia New Zealand, 2023) regulates the safety and standards for food products. It also prescribes the pre-market safety assessment that must occur prior to producing novel microalgae derived products for human consumption.
- **Animal feed ingredients:** The *Agricultural and Veterinary Chemicals Code Act 1994* (Australian Government, 1994) regulates what chemicals can be used in the production of animal feeds. The *Australian New Zealand Food Standards Code* will also apply to ensure the safe use of novel products. *Australian Standard AS 5812:2023 Manufacturing and marketing of pet food - Cats and dogs* provides requirements for the manufacture and marketing of pet food intended for consumption by domesticated cats and dogs (Standards Australia, 2023).

3. Health and safety standards

The *Coal Mining Health and Safety Act 1999* (Queensland Government, 1999) regulates the operation of coal mines “to protect the safety and health of persons at coal mines and persons who may be affected by coal mining operations, and for other purposes.” The Act (Division 3) requires any on-site activity to comply with a site’s Safety and Health Management System (SHMS). An algae cultivation and processing operation is considered an on-site activity under the current legislation. Pastoral activities undertaken within the mining lease are the only commercial activity the Act excludes from consideration as an “on-site activity” (Part 1, Section 10) (Queensland Government, 1999).

The conditions imposed by a SHMS reflect the hazardous nature of coal mining as well as the harsh penalties that flow to those who have responsibility for the death or injury of onsite workers. The onerous nature of its requirements will impose costs that may make it challenging to achieve a commercially viable algae-based entity. The costs include, but are not limited to:

- **Meeting coal mining competencies:** The commercial operation will need to recover the costs of both its employees and contractors obtaining and maintaining their coal mining competencies. For example, each employee and subcontractor must obtain, at a minimum, a Standard 11 (S11) *Mining Induction Certificate* and pass a *Queensland Coal Board Medical* every three years.
- **Site inductions:** All staff and contractors must undertake the site inductions relevant to their work activities.
- **Pit license:** If a mine is unable to provide escorted transport, employees required to access mine pits will need to gain and maintain their site pit license.
- **Mine-spec vehicles:** Access to the commercial operation will require the leasing of mine-spec vehicles which are considerably more expensive than a standard 4WD vehicle.
- **Equipment satisfies site inspection requirements:** All machinery and electrical equipment require site inspection prior to being used in the operation.
- **Algal cultivation facility operational SHMP:** The entity will be obliged to develop its own SHMP for approval by the mine’s Site Senior Executive for its integration within the site SHMS. This SSE will also require a separate SHMP for approval by each contractor engaged by the commercial entity. Compliance with the existing SHMS will impose costs on the enterprise that it would unlikely incur outside the lease area. For example, all SHMS reviewed within this project will require the SHMP to include:
  - A minimum of two people present whenever undertaking work on or near water.
  - Meeting of incident and near miss reporting thresholds.
  - Blood alcohol testing prior to accessing the worksite.
- **Personal Protection Equipment (PPE):** Employees and contractors will be required to wear clothing, hard hats, and boots that comply with site requirements.

The requirement to use contractors who meet site competency requirements within remote areas narrows supply and therefore increases the cost of services.

4. Biodiversity and Ecosystem Protection

In Queensland, all land disturbed during mining is to be progressively rehabilitated to a stable condition after mining. Land is in a stable condition if (a) the land is safe and structurally stable, and (b) there is no environmental harm being caused by anything on or in the land, and (c) the land can sustain a PMLU (section 111A of the Environmental Protection Act 1994 (Queensland Government, 1994)). The provision of habitat or ecosystem services are recognised as a PMLU in the progressive rehabilitation and closure planning framework (Department of Environment, Science and Innovation, 2024d). However, there is uncertainty around what level of ecosystem value is considered a valid PMLU.

As is the case in non-mining contexts, a microalgae-based operation will have General Biosecurity Obligations under Queensland’s *Biosecurity Act 2014* (Queensland Government, 2014) to prevent introduced strains from escaping into or negatively impacting the environment and water bodies. This Act will also require the operator to put in place risk management practices and monitor where the introduced strains are cultivated, and to report any biosecurity threats that arise. Where possible, it would seem beneficial for an operation to invest in the isolation, application and optimisation of native strains already present in mine void water.

3.7 Best practices rehabilitation planning and regulatory requirements to implement algae-based technology at mine sites

3.7.1 Rehabilitation guidelines

In Australia, mining rehabilitation is governed by several regulatory frameworks and guidelines to ensure environmental restoration and compliance with land-use agreements (Manero et al., 2020). These guidelines provide a framework for the systematic recovery of ecosystems, including the stabilisation of mine waste, restoration of vegetation, and improvement of water quality. Rehabilitation guidelines are generally clearly defined within the operating territories and can also be part of Indigenous Land Use Agreements. Rehabilitation planning may go side by side with the development of a commercial algae process, and in many cases, the two efforts may be mutually beneficial, where algae cultivation may be directly integrated into rehabilitation efforts. This approach not only accelerates the ecological recovery of the mining site but also establishes a commercial process that generates revenue, making rehabilitation efforts economically sustainable. However, the dual nature of the operations would also bring the potential regulatory challenges, for example, in aligning the timelines and objectives of rehabilitation and algae commercialisation. Rehabilitation efforts are often subject to strict timelines and monitoring to ensure that the site meets post-closure environmental standards. Commercial algae cultivation, which may take time to scale, will need to operate within these rehabilitation schedules. The parallel development of rehabilitation planning and a commercial algae process is feasible and, in fact, advantageous for achieving optimal best-practice outcomes. However, careful coordination with environmental regulations, community engagement, and water use compliance would be necessary. Anticipating and addressing these regulatory challenges early on will ensure smooth integration and long-term success for both rehabilitation and commercial operations.

3.7.2 Regulatory database

As mentioned above (Chapter 3.7), regulatory requirements are a crucial consideration to ensure that algae cultivation at mine sites complies with environmental, safety, and operational standards. However, due to the innovative nature of the concept, relevant regulations might not be in place yet, or it might be unclear which regulations are applicable. To mitigate resulting operational risks prior to commencement, a recommended phase within the context of further development would be the assembly of a regulation database, consisting of government, industry and societal regulations that impact algae biomass production, its processing and product formation specifically at mine sites. Such a database will support industry to identify regulatory barriers (e.g., operational zoning, land-use) and opportunities (carbon accounting and pricing, biodiversity enhancement, organic classification). An early understanding of the regulatory landscape will provide industry with a competitive edge in biomass production, downstream processing and product development. Such a database could comprise a compendium of regulatory information and contact points to assist industry to bring their technologies and products to market. Furthermore, engaging with government, environmental organisations and traditional owners will ensure long-term viability and acceptance of algae-based technologies in the mining industry.

4. Business case

4.1 Economic, social and environmental benefits from algal cultivation at mine sites

The application of algal technologies at mine sites offers significant economic, social, and environmental benefits, all of which can be quantified through various metrics. Economic impacts can be assessed through revenue generation, cost savings, and carbon credit valuation. Social benefits are measured in job creation and community engagement, while environmental impacts are quantified through improvements in water quality, biodiversity, and carbon sequestration. By integrating these benefits into a comprehensive assessment, stakeholders can better understand the value of algae in the mining context. Various benefits and methods of quantification are shown in Table 13.

Table 13: Overview of economic, social and environmental benefits that can be obtained by algae cultivation at mine sites, with methods for quantification.

Benefit category	Benefit type	Quantification
Economic	**Revenue generation:** Algae cultivation at mine sites can generate additional revenue streams through the production of biofuels, bioplastics, fertilisers, and animal feed. These products can be sold into various markets, including energy, agriculture, and aquaculture.	Economic benefits can be quantified by calculating the revenue generated from the sale of algal products, factoring in production costs, market prices, and the scale of operations through a techno-economic analysis. A further cost-benefit analysis can compare these revenues against the initial investment and operational expenses, and potential cost-savings.
	Carbon credits: Algae can sequester CO_2 from mining operations, enabling companies to generate carbon credits. These credits can be sold in carbon markets or used to offset the company's emissions, potentially leading to cost savings.	The economic value of carbon credits can be quantified by multiplying the amount of CO_2 sequestered by the current market price of carbon credits or comparing to the cost of non-compliance to emission reduction targets.
	Cost savings on rehabilitation: Algal technologies can be integrated into mine site rehabilitation, potentially reducing the costs associated with traditional remediation methods.	Cost savings can be quantified by comparing the expenses of algae-based rehabilitation techniques with those of conventional methods. This could include savings from reduced chemical use, lower labour costs, or reduced need for long-term monitoring.
Social	**Job creation**: The establishment of algae cultivation systems at mine sites can create local jobs, particularly in rural or remote areas where mining operations are typically located.	Social benefits can be quantified by assessing the number of jobs created and the economic impact on local communities. This can include direct employment in algae cultivation and processing, as well as indirect employment in associated services.
	Community engagement and development: Algae projects can involve local communities, including First Nations groups, in cultivation, processing, and the distribution of products. This can lead to skill development, economic empowerment, and stronger community ties.	The social impact can be quantified by measuring the economic upliftment of communities through income generation, educational opportunities, and increased participation in sustainable practices.
Environmental	**Pollution reduction**: Algal technologies can be used to treat contaminated mine water by absorbing heavy metals and nutrients, improving water quality before it is discharged into the environment.	Environmental benefits can be quantified by measuring the reduction in pollutant concentrations (e.g., heavy metals, nitrates) in treated water compared to untreated water. This can be done through regular water quality monitoring.

Benefit category	Benefit type	Quantification
	Biodiversity enhancement: By improving soil and water quality, algae-based rehabilitation can support the re-establishment of native vegetation and wildlife, enhancing biodiversity at and around the mine site.	Biodiversity benefits can be quantified through ecological surveys that track changes in species diversity, abundance, and habitat quality over time.
	Carbon sequestration: In addition to generating carbon credits, algae cultivation directly contributes to carbon sequestration, reducing the overall carbon footprint of mining operations.	The amount of carbon sequestered can be calculated based on the biomass produced and the carbon content of the algae. This can be expressed in tons of CO_2 sequestered annually.

4.2 Estimate on the costs of setting up algal growth systems and achievable algal biomass growth yields

Examples of algal growth rates in acidic growth media have been shown in Section 2.2.3 "Selection process for algal species and systems",

Table 2. Some of these examples used media intended to replicate the composition of acid mine drainage. There are very little data in the literature regarding growth rates of algae using actual mine water, particularly at large scale. This appears to be a significant gap in the current knowledge which requires further study through laboratory experiments and a pilot trial under more realistic conditions to ascertain achievable growth rates. Until these data become available, cost estimates need to rely on other published examples of techno-economic assessments and estimates of production costs, keeping in mind that there may be significant uncertainties in these estimates.

Estimating yields of algal biomass and products, as well as associated capital and operating costs is highly complex, and requires dedicated investigation. Various techno-economic studies have been published, which estimate algae production costs based on the input of many process and economic variables, such as climate data, strain selection, assumed productivities, harvesting and downstream processing technologies, production scale, product yield, equipment and consumable costs, labour, taxes, and electricity. An example of the complexity of all such model considerations is also shown in Figure 27, which is an example of a process flow diagram and model inputs for a biodiesel production process. The reliability of the estimations is however only as reliable as the input data and the assumptions on which the models are based, and as such, published ranges of production costs vary significantly from highly market competitive to completely unfeasible.

Any costs for algae production systems as well as algae products are cited in AU$, and where needed have been converted from the original currency using the data available at https://www.ato.gov.au/tax-rates-and-codes/ and adjusted for inflation using the online calculator at www.rba.gov.au/calculator/.

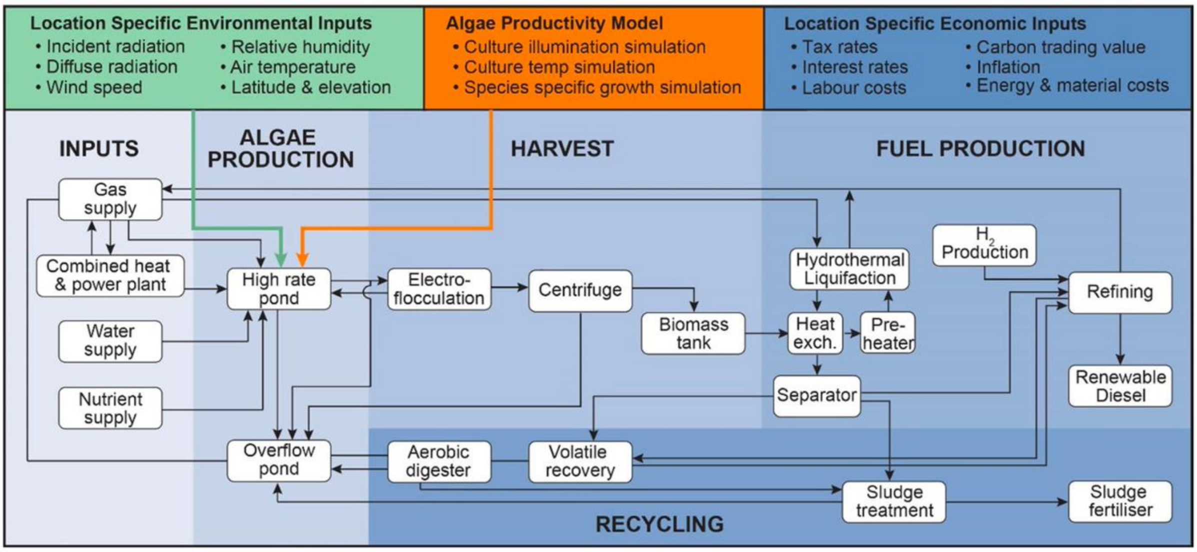


Figure 27: Microalgae-based renewable diesel production process flow diagram and model inputs (Reused from Roles et al., 2021 with Creative Commons License 4.0).

International Location Specific Environmental Inputs (green) and the Algae Productivity Model (orange) connect with the high-rate pond module of integrated techno-economic and life-cycle analysis (TELCA), to enable location, system, and strain specific growth modelling (1 h temporal resolution). Location Specific Economic Inputs (blue, top right) influence the final minimum diesel selling price and internal rate of return.

In general terms, closed photobioreactors, especially tubular systems, are significantly more expensive than open raceway ponds, leading to higher CapEx for the former. However, higher levels of process control, and cleaner production, do lead to increased productivities and quality biomass which can be used for higher value products thus enabling a higher price. For a single strain, Schipper et al. (2021) estimated biomass productivities could vary between 36 and 74 metric ton ha^{-1} $year^{-1}$, depending on reactor configuration and location within the Middle East (similar climates to certain regions in Australia) (Schipper et al., 2021). Scale of facility also has significant impact on costs. Up to 67% reduction in costs can be achieved through an increase of scale from 1 ha to 10 ha of pond area. Under optimistic scenarios for input assumptions, the cost of algae production is estimated to be AU$ 4.42 per kg for open raceway ponds, and AU$ 7.46 per kg for closed photobioreactors (Schipper et al., 2021).

Ruiz et al. (2016) also investigated the costs of various product/biorefinery routes with associated downstream processing for various global locations, showing a very high variability, ranging AU$ 0.61-6.55 per kg of biomass, added on top of the biomass production costs. This 10-fold difference clearly shows how choices of product and associated biorefinery process options can make or break the economic feasibility of the process (Ruiz et al., 2016).

Vázquez-Romero et al. (2022) assessed various strain and processing options, resulting in a large range of productivities and production costs, and estimated revenues, showing potentially competitive costs for functional foods, food, and feed additives, specialised aquaculture products and other high value applications (e.g., cosmetics) (Figure 28) (Vázquez-Romero et al., 2022).

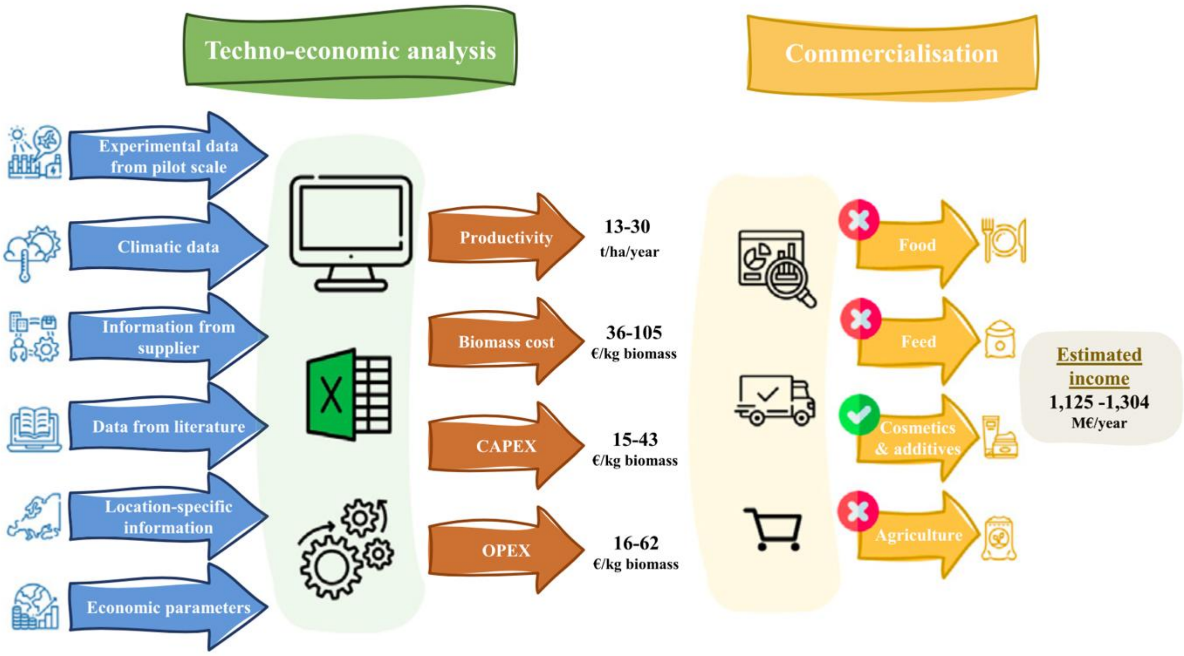


Figure 28: Various required inputs, process design and product choices all impacting final techno-economic feasibility (Reused from Vázquez-Romero 2022 with Creative Commons license 4.0).

Examples of algal production cost estimates with various growth systems are shown in Table 14. It is worth noting that apart from the study by Alavianghavanini et al. (2024), these studies are based on growth rates on synthetic media with a range of culture systems including closed photobioreactors and raceway ponds for a variety of locations outside Australia. Under optimised growth conditions in a tubular photobioreactor, Acién et al. (2012) found dried algal biomass production cost to be AU$ 89.77 –109.83. Ruiz et al. (2016) forecasted lower costs across a range of reactor setups and site locations, at AU$ 5.43 - 19.27 kg^{-1} of dry biomass. In comparison a more recent techno-economic analysis by Alavianghavanini et al. (2024) considering the data from Shayesteh et al. (2021) using raceway ponds and a nutrient-rich wastewater medium, dewatering the algal biomass via centrifuge to 100 - 200 g L^{-1} concentration rather than freeze-drying found a production cost of approximately AU$ 2.76 - 12.40 (figures converted from US$). It is worth noting that further drying of the biomass may incur further costs in the case of the latter example cited here, however the downstream processing might not necessarily require a completely dried product or may involve additional post-harvest processing beyond simply drying.

Table 14: Algal production (cultivation and harvesting) costs (CapEx + OpEx) using various cultivation systems.

Growth system	Biomass product	Production cost per kg		Currency (year)	AU$ (2024) per kg[1]		Reference[2]
		min	max		min	max	
Horizontal tubular photobioreactor	Dry biomass	56.40	69.00	€ (2012)	89.77	109.83	Acién et al., 2012[a]
Flat panel photobioreactor	Dry biomass	3.10	6.00	€ (2016)	5.43	10.51	Ruiz et al., 2016[b]
Vertically stacked horizontal tubular photobioreactor		4.60	8.30		8.06	14.54	
Horizontal tubular photobioreactor		4.80	8.90		8.41	15.59	
Raceway pond		4.00	11.00		7.01	19.27	
Raceway pond	100-200 g L^{-1} paste	1.80	8.10	US$ (2024)	2.76	12.40	Alavianghavanini et al., 2024[c]

[1] Currencies were converted from original currency to AU$ using the data available at https://www.ato.gov.au/tax-rates-and-codes/ and adjusted for inflation using the online calculator at https://www.rba.gov.au/calculator/

[2] Culture media and species (where known) are:

[a]: Trial culture of *Scenedesmus almeriensis* using ten 3 m^3 tubular photobioreactors with synthetic growth media performed in Almería, Spain (Acién et al., 2012),

[b]: Data on unspecified non-genetically modified organism (non-GMO) microalgae tested at AlgaePARC facility Netherlands with projections calculated for locations including The Netherlands, Canary Islands, Turkey, Curaçao, Saudi Arabia and south of Spain (Ruiz et al., 2016),

[c]: Trial of *Scenedesmus* sp. grown in anaerobically digested abattoir effluent (wastewater) using open raceway ponds in Perth, Australia (Alavianghavanini et al., 2024).

Rather than looking at production costs per kilogram of algal biomass, setup may be forecast on a surface area basis of infrastructure to be installed. Roles et al. (2021) have performed techno-economics evaluation forecasting associated with algal production oriented toward high density liquid fuel as the end-product. For a large-scale pond facility at approximately 500 hectares total area, forecasts found values approximately AU$ 560 ± 175k for expected Capital Expenditure (CapEx) and AU$ 36k ± 13k Operating Expenditure (OpEx) per hectare (US$ 2021 values have been converted and adjusted for inflation to AU$ 2023 values). These figures also include harvest and liquid fuel extraction processes which account for approximately half the cost in some scenarios. Species used in the assessment were high-saline tolerant *Dunaliella tertiolecta* and *Nannochloropsis oceanica* and the assessment looked at 12 geographical locations across North and South America, Europe, Africa, the Middle East, India, Asia and Oceania. This study highlighted site location as one of the most important considerations due to growth rates depending on the environmental conditions such as solar radiation, temperature and evaporation. Again, this study has many factors which differ compared to an algal mining wastewater treatment process, however, may serve as a guideline to the types of factors and expense anticipated when looking at installing an algal culture facility (Roles et al., 2021).

4.3 Market opportunities and economic potential for revenue generation from the use of algal biotechnologies at mine sites

4.3.1 Algal product markets and value

The global algae market is experiencing rapid growth, driven by the increasing demand for sustainable and versatile products across multiple industries. Algae are used in a variety of sectors, including food and beverages, nutraceuticals, animal feed, biofuels, cosmetics, and pharmaceuticals. Due to its diverse use, the exact size of the algae products market is difficult to estimate as a whole. (IMARK, 2024) valued it at AU$ 2.9 billion in 2023 with an expected compound annual growth rate (CAGR) of 4.8% over 2024-2032 to AU$ 4.5 billion, whilst (Markets and Markets, 2024a) reported a 2023 value of AU$ 8.0 billion with a growth rate of 6.4% to AU$ 11.0 billion in 2028 – a significant difference (Figure 29). Overall, the growth is fuelled by the rising consumer demand for natural and eco-friendly products, advancements in algae cultivation technologies, and the increasing focus on sustainability. Algae's ability to produce high-value compounds such as omega-3 fatty acids, proteins, and biofuels positions it as a key player in the future bioeconomy, with significant opportunities for revenue generation in both established and emerging markets.

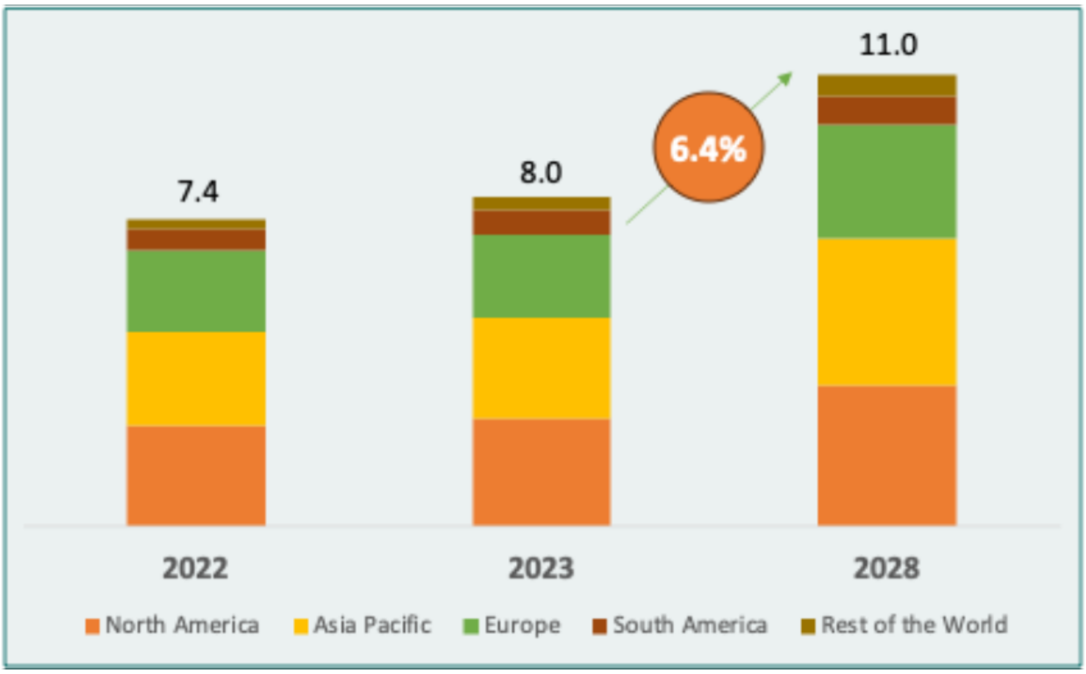


Figure 29: Global algae products market forecast in AU$ billion (Adapted from Markets and Markets, 2024a).

Mines have many opportunities to generate revenue from microalgae, but these options must be carefully evaluated. The opportunities with the highest feasibility include wastewater treatment and bioremediation, carbon capture and sequestration, and biofertiliser and soil amendment production. Other options, such as the production of high value bioproducts or commodity products such as biofuels can also be investigated based on the characteristics (composition, quality) of the algae biomass produced. Although these options could potentially generate higher revenues, technologies are more immature and higher risks (investments) are involved. Table 15 provides an overview of the various market opportunities, including possible revenue streams, market value, and looking into overall expected feasibility of algae cultivation within a mining context. The product market values are of the whole global markets, not only algae-based, unless specifically mentioned.

Table 15: Overview of algae-based products with potential application within mining contexts, with market values and estimated feasibility.

Description		Market size / Value[1]		Feasibility	Reference
Wastewater Treatment & Bioremediation	Applying algae-based bioremediation or biosorption to remove heavy metals, nutrients, and other pollutants from mining wastewater.	N/A		**High**: established technology; regulatory pressures and environmental mandates make this a critical need for mining companies, and it could save on costly traditional wastewater treatment methods.	
Carbon Capture and Sequestration	Utilising algae to capture CO_2 emissions from mining operations.	Australian Carbon Credit Unit (ACCU) Value: 34-75 AU$ ton^{-1} CO_2 equivalent		**High**: using algae to capture CO_2 emissions is well established, with proper process design. Selling carbon credits or participating in carbon trading markets can provide significant revenue streams.	Australian Government Clean Energy Regulator, 2024a; Hatfield-Dodds and Boulus, 2023
Soil Amendments	**Biofertiliser** used as organic fertilisers in agriculture.	Market size: AU$ 18.7 billion (2023)* with CAGR of 10.3% (2024-2033) * Microalgae-based fertiliser only	45-90 AU$ kg^{-1}	**High**: demand for organic agricultural products is growing, making it an attractive market. Biofertiliser can also be used internally for mine site rehabilitation, supporting CSR profiles.	Shivarkar, 2024; Research Nester, 2024b; Zou et al., 2021
	Biostimulants can improve nutrient uptake by plants and soil structure and aeration, stimulating root growth.	AU$ 6.5 Billion (2024) with CAGR of 12.0% (2024-2029)		**Medium-High:** growing drive for organic farming as well as maximising crop returns is driving the interest in biostimulants, making it an interesting market.	Markets and Markets, 2024b; Ferreira et al., 2021
	Biochar effective in soil enhancement and pollution remediation.	Market size: AU$ 11.9 million (2023) with CAGR of 14.1% (2023-2033)	451-2257 AU$ ton^{-1}	**High**: although revenue streams might be limited, pressure from government and local communities is high to restore lands post mining closure. Algae could be a cheaper option compared to others, with added benefit of potential carbon credits.	Fact.MR, 2023a

Description		Market size / Value[1]	Feasibility	Reference
	Dust Suppressant: Algal biomass or derived biopolymers could be formulated into biodegradable dust suppressants. These materials are capable of retaining moisture and binding dust particles**.**	Market Size AU$ 11.6 Billion (2022) with CAGR of 5.5% (2023-2033)	**Medium:** local application within mining contexts would replace need to purchase external products and/or reduce water usage and environmental impact of current solutions. Regulatory limitations would need to be investigated, and production costs would need to be low to be able to compete with current solutions.	Fact.MR, 2023b; Adams, 2022; Wang et al., 2023
Animal Feed	**Livestock feed** added to the feed of livestock, such as poultry, pigs, and cattle, a valuable supplement to traditional feed.	AU$ 6.5 Billion (2023)* with CAGR of 4.1% (2023-2030) * Microalgae-based animal feed only	**Medium:** growing demand for sustainable feed options can make this a lucrative market, and although the technology is established, product quality (presence of toxic elements), production costs, and regulatory requirements need to be considered.	Persistence Market Research, 2024
	Aquaculture Feeds: Nutrient-rich feed for fish and shellfish, improving growth, health, and sustainability in aquatic farming systems.	AU$ 421 Million (2023)* with CAGR of 7.5% for 2024-2034 * Microalgae-based aquafeed only	**Medium-high:** microalgae-based aquafeed is becoming a promising and sustainable solution for the aquaculture sector. Not only does it support in meeting the escalating demand for fish protein, but also reduces the environmental footprint of aquaculture operations.	Choudhury, 2024
	Pet Food: offering proteins, omega-3 fatty acids, and antioxidants that support the health and well-being of pets.	AU$ 3.6 million (2023)* with CAGR of 5% (2024-2033) * Microalgae-based petfood only	**Medium-high:** The pet food market is shifting towards more sustainable, natural ingredients, creating interesting opportunities with potentially higher prices compared to livestock feed. Consumer acceptance will be crucial to increase market size.	Choudhury, 2021
	Specialty Feeds: feeds for specialty markets, such as feed for bees or other insects.	N/A	**Low**: high risk, low volume market. Could be considered in a biorefinery as side product.	

Description		Market size / Value[1]		Feasibility	Reference
Biopolymers and nanomaterials	**Nanocellulose:** used in high-value applications such as bio composites, packaging, electronics, and medical materials due to its strength, lightweight properties, and biodegradability.	AU$ 642 million (2023) with CAGR of 21.3% (2024-2036)	AU$ 3010 - 15,051 ton^{-1}	**Low:** Specific algal strains rich in cellulose would need to be identified and optimised for production in mining environments, and extracting nanocellulose can be technically challenging, where the cost of advanced processing technologies could be a barrier to scalability.	Research Nester, 2024c
	Polyhydroxyalkanoates – PHAs: Derived from algal biomass, to be used as biodegradable alternatives to conventional plastics.	AU$ 140 million (2023) with CAGR of 15.9% (2023-2028)	AU$ 6-11 kg^{-1}	**Medium-Low:** although the demand for bioplastics will increase significantly, also driven by policy changes, the production technology from algae is still immature and not yet market ready.	Markets and Markets 2024d; Berry et al., 2022
	Alginate: food additive (stabiliser, thickener, and emulsifier in various food products).	AU$ 1.4 billion (2023) with CAGR of 5.7% (2024-2036)		**Medium-low:** although the market is growing, only specific algae can be used for alginate production, which could not be compatible with cultivation within mining contexts.	Research Nester, 2024a
Algal Pigments	**Astaxanthin:** This high-value antioxidant is used in aquaculture and animal feed (46.4% of total market), but also for dietary supplements, nutraceuticals, and cosmetics.	AU$ 3.5 billion (2023) with CAGR 17.1% (2024-2030)	AU$ 2,257 – 9,030 kg^{-1}, depending on purity and source	**High:** growing demand for astaxanthin is being fuelled by its increasing use various industries. Residual biomass can be sold as fertiliser, further improving economic feasibility. Largest growth is expected in Asia-Pacific region.	Grand View Research, 2024b; Banerjee and Ramaswamy, 2022; Panis et al, 2016
	Beta-Carotene: Used in food colorants, nutritional supplement, cosmetics, animal feed. Algae constitute of 33.9% of	AU$ 768-907 million (2023) with CAGR of 4.8-7.1% for 2024-2030	AU$ 450-4500 kg^{-1} depending on purity and source	**Medium-Low:** could have economic potential if premium quality can be obtained. Especially interesting in hypersaline mine waters. There would be the need to compete with synthetic beta-carotene – although demand for natural sources is on the rise. Regulatory constraints could also have an impact.	Research and Markets, 2023a; Research and Markets, 2024; Research Markets, 2024; Research and Markets, 2023b

Description		Market size / Value[1]		Feasibility	Reference
	the beta-carotene global market (2023).				
	Chlorophyllin: food colouring, cosmetics, nutraceuticals, and pharmaceuticals, particularly for its antioxidant and anti-inflammatory properties.	AU$ 411 million (2023) with CAGR of 7.94%	AU$ 54-298 kg^{-1} (depending on purity)	**Medium-low**: Although strain requirements are broad, extraction and processing are complex and costly, especially in remote locations. Market is small and price is lower compared to other product such as lutein or beta-carotene.	Verified Market Reports, 2024; Karan et al., 2023
	Phycocyanin: for use in dietary supplements, nutraceuticals, therapeutic products, and food colour processing.	AU$ 1.1 billion (2022) with CAGR 7% (2023-2033)	AU$ 288-864 kg^{-1} or even higher (depending on purity)	**Medium-high**: Phycocyanin can collect high prices (depending on purity), and production is well established. Cultivation conditions (water and environmental) however will have a large impact on product yields.	Markets and Markets, 2024a; Rito-Palomares et al., 2001
	Lutein: used in food and beverage industry as natural colorant and in dietary supplements for its antioxidant properties.	AU$ 558 million (2023) with CAGR of 5.6%	AU$ 753-1806 kg^{-1}	**Medium**: Production will have specific strain requirements, possibly requiring amendments to mine water for cultivation. Processing and extraction methods are complex and expensive, and remote location of mining operations could present logistical challenges. Stringent regulatory standard will need to be complied with.	Markets and Markets, 2024c
High-Value Bioproducts	**Omega-3 Fatty Acids:** can be used in nutrition but also for aquaculture and pet food industries.	AU$ 3.9 billion (2023) with CAGR of 7.9% (2024-2030)	AU$ 150 – 452 kg^{-1} depending on concentration and purity	**Medium**: large and growing market is of interest, however strain specificity, cultivation requirements for high product yields, and product extraction requirements could make production economically unfeasible.	Grand View Research 2024c
Biofuels	**Biodiesel:** Produced from algal lipids, it is considered a promising alternative to fossil fuels.	AU$ 13.8 Billion (2023), CAGR 10.1% (2023-2030)	US$ 0.85 - 1.00 L^{-1}	**Medium-Low:** generating renewable energy can create a profitable market, especially with increasing demand for sustainable energy sources. Although converting algae into biofuels is technologically feasible, it is currently not cost-competitive with fossil	Grand View Research 2024a; Branco-Vieira et al., 2020

Description		Market size / Value[1]		Feasibility	Reference
	Bioethanol: Another biofuel option from algae, used in blending with gasoline.		AU$ 0.80 - 1.10 L^{-1}	fuels. Cost reductions could be accomplished by integration within a biorefinery value chain as well as scaling up production, and policy changes can also further support feasibility.	
	Bio-Crude Oil: concentrated, synthetic bio-oil substitute for petroleum crude oil, which is produced using thermochemical conversion of biomass.				

[1]Market values are of total global product market (not only algae-based), unless mentioned otherwise. N/A = not available; ACCU = Australian Carbon Credit Unit; CARG = Compound annual growth rate.

The most immediate and logical application of algae-based processes for mine-sites both prior and post closure, is the treatment of wastewaters resulting from mining activities, such as AMD and pit lakes. Regulatory pressures and environmental mandates make this a critical need for mining companies, and combining this need with revenue generating activities would increase economic feasibility. Most apparent co-applications would be carbon capture (inherent to most algae processes), and production of at least one product for revenue generation. The type of water used, the types of algae strains, as well as the way in which algae are used (active or passive microalgae treatment) will determine the biomass quality, which in effect will determine possible product options. Soil amendment production (either as biofertiliser or bio-char), are interesting options for further exploration due to their direct applicability on site to meet further targets of mining sites for land rehabilitation and ecosystem restoration.

4.3.2 Technology and policy strategies to support algae product commercialisation

Current production costs for many algal products, particularly fuels, remain higher than prevailing market prices, posing a significant barrier to direct market entry. While smaller niche markets may offer cost-competitive production scenarios, their limited size cannot accommodate the ambitious, large-scale targets associated with algae implementation in mining operations. This discrepancy risks creating an oversupply, which could destabilise market dynamics. As a result, identifying viable pathways to market becomes a critical factor, ensuring that production aligns with demand and supports the sustainable growth of algae-based solutions in the mining sector.

Various studies have underscored that for bulk algae products to become cost competitive, multi-product biorefineries will allow compensation of current production costs to achieve profitability (Rajesh Banu et al., 2020). For example, Karan et al. (2023; 2022) investigated the techno-economic potential of multiple biorefinery options (4 product: chlorophyllin, lutein, protein, and biofuel feedstock, and 2 product: protein and biofuel), demonstrating a competitive bioproduct valuation in line with current market prices – something unachievable when targeting the individual components as sole products. Kruger et al. (2022) and Wang et al. (2022a) both found that integrated production of various biofuels, thereby valorising various fractions of the algae biomass, could reduce the minimum fuel selling price to market competitive values. Ruiz et al. (2016) aptly illustrated how the compounded market value of algae biomass increased the biomass market price to potentially cost-competitive numbers. Karan et al. (2022), however, also underscored that improving cost-competitiveness will also rely on incremental optimisations of biological and operational systems, as well as favourable financial and policy conditions, and not in all cases will a biorefinery approach increase revenue.

Within a mining context, the selected product, or suite of products produced will be leading in determining the best way to market. Keeping the production costs as competitive as possible will be leading in achieving market access, and would be driven by technical refinement, improving production processes and productivities, supported by favourable policy advances and financing options. However, the largest benefits will most likely result from the adaptation of a multi-product biorefinery approach. Such an approach could potentially even be centralised, linking multiple co-located mines to a centralised conversion plant with various processing options (Klein et al., 2023). This would also help avoid overwhelming markets with a single product, offering a diverse portfolio of bioproducts to consumers.

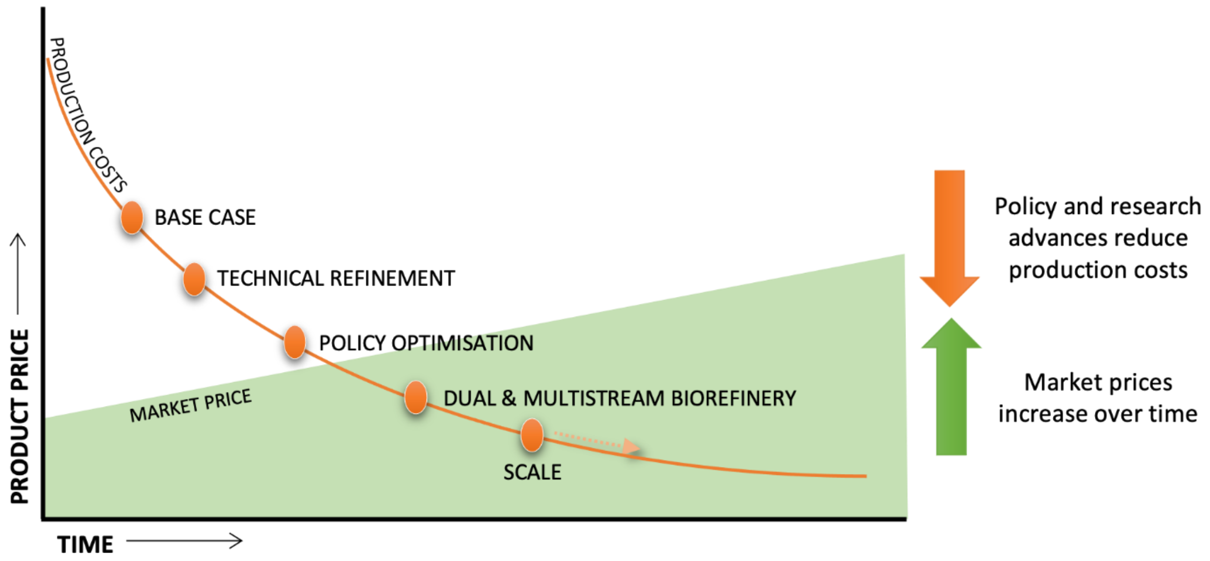


Figure 30: Evolution of production costs through various stages of refinement and improvement, compared to ever increasing market prices.

4.3.3 Linking potential algal producers with end-user markets

There is a broad spectrum of end-users that could benefit from algae production at mining sites, with the mining industry itself being a primary beneficiary. Algae-derived products, such as biochar, can be locally applied for mine site rehabilitation, enhancing soil quality and stability. Additionally, algae's dust suppressant properties offer practical applications for controlling dust in mining areas. The carbon credits generated from algae cultivation could be used by mining companies to offset their emissions or sold to create additional revenue streams.

Beyond internal uses, the success of linking algae producers with end-user markets hinges on identifying industries with a growing demand for sustainable, bio-based products. Strategic partnerships with sectors like agriculture, energy, and pharmaceuticals, which are increasingly shifting toward green alternatives, can maximise the economic potential of algae cultivation.

The Centre for Solar Biotechnology at UQ, Murdoch University, and CSIRO have extensive industry and researcher networks with diverse capabilities, which can play a crucial role in integrating algae production into various value chains. These networks, coupled with collaboration across industries and research institutions, can attract governmental support, especially from those seeking to meet sustainability and emissions targets. Focusing on high-value markets, supported by innovation and strong partnerships, will be critical to fully realising the market potential of algal products in the mining context.

The challenges will be largely dependent on the final proposed use of the biomass (product), and associated markets, as well as locations. When used for consumer goods, products derived from algae grown in post-mining contexts will face strict regulatory scrutiny, particularly regarding the potential presence of heavy metals or other contaminants. Obtaining necessary certifications for safety and environmental standards could be challenging and time-consuming. Furthermore, market acceptance would face the same scrutiny, as end-users may be unfamiliar with or sceptical of algae-based products derived from mining contexts, particularly concerning quality, safety, and sustainability. Furthermore, depending on the application of the algae biomass, establishing a reliable and integrated supply chain between algae producers at mine sites and end-user markets could be complex seeing the generally remote nature of mine sites. Local application of the end-products would remove this complexity but would require all downstream processing to be located on site, rather than at a centralised location.

Industrial integration for algae cultivation at mining sites can be achieved by creating symbiotic relationships with nearby industries that generate resources critical for algae growth. For instance, power plants and manufacturing facilities generating flue gas enriched in CO_2 can capture and supply CO_2 to feed algal systems, reducing their own carbon footprint while supporting algae cultivation. Wastewater treatment plants, agricultural operations, and aquaculture facilities can provide nutrient-rich waste streams, like nitrogen and phosphorus, that are essential for algal growth. In return, algae can assist in purifying wastewater, producing biofertilisers for agriculture, or generating biofuels for energy use, creating a circular economy model. These integrated operations can reduce waste, improve resource efficiency, and create economic value across multiple sectors.

4.3.4 Carbon credits

Australian mining companies must reduce carbon emissions as part of national and international climate commitments, with specific reduction pathways established through the Safeguard Mechanism and investor expectations. The Safeguard Mechanism applies to large industrial emitters, including mining companies, that emit over 100,000 tons of CO_2 equivalent (CO_2-e) per year. This mechanism sets baselines for emissions and requires companies to reduce emissions or purchase carbon credits if they exceed their baselines. The general target aligns with 4.9% reduction per year until 2030, and net-zero by 2050, but company-specific targets can vary. In some of the survey responses, it was mentioned that some mining companies are currently purchasing carbon credits to meet regulations.

The potential carbon credits achievable from algal CO_2 capture at mine sites could be significant, depending on the scale of the operation, the efficiency of the algae in sequestering CO_2, but will be impacted (reduced) by the algae production process itself. During growth, algae can capture and sequester approximately 1.8 kg of CO_2 kg^{-1} of dry algae biomass produced (Souza et al., 2024) – thus an algae system producing 1,000 metric tons of dry algae biomass annually could theoretically capture 1,800 metric tons of CO_2 per year. This calculation, however, does not consider the (indirect) CO_2 emissions associated with energy requirements for construction and operation of an algae production facility, nor that associated with the supplied nutrients. These could however lead to the whole algae production process being a carbon source rather than a carbon sink (Zhang et al., 2023b). Therefore, efforts should focus on improving the energy efficiency of microalgal systems, such as the use of solar energy, but also nutrient recycling from waste streams, to reduce the carbon footprint of microalgal cultivation, helping it become carbon neutral or negative, to be able to generate value from carbon credits. A detailed LCA study would be warranted to estimate the actual carbon credit of the algal process.

The ‘value’ of captured CO_2 depends on the carbon credit price, which can vary widely. In Q1 2024 the market value of Australian Carbon Credit Units (ACCUs) was approximately AU$34 per metric ton of CO_2-e (Australian Government Clean Energy Regulator, 2024a). This value is expected to rise, driven by strong demand from both government initiatives and commercial buyers who need to meet compliance obligations as more companies adopt net-zero commitments and seek carbon offsets as part of their strategies (Goliya, 2023; Moore, 2023). As of such, Ernest & Young expects the prices of ACCUs to double to approximately AU$75 before 2035 (Hatfield-Dodds & Boulus, 2023). This would put the theoretical potential revenue (before considering process-related emissions, i.e. assuming the use of carbon-neutral electricity sources to power the algae process) from carbon credits for an algae production facility producing 1,000 metric tons of biomass per year at AU$61k-135k annually. This benefit is in addition to the consequence of not taking any action to reduce emissions, which would require purchasing of ACCUs available on the market to compensate for exceeding the baseline or incur significant financial penalties of AU$275 per metric ton of excess emissions (Australian Government Department of Climate Change, Energy, the Environment and Water, 2024).

There are however also other factors influencing carbon credit generation which need to be considered, first and foremost the proposed use of the biomass. Most products from microalgae, such as food, feed, and fuels, would re-emit the captured CO_2 to the atmosphere during use and degradation, and as such the CO_2 captured during production would not qualify for carbon credits. Long-term sequestration products from algae are few, however some are very applicable within the current context of mining. The use of algae as a feedstock for biochar production and subsequent soil amendment could entrap carbon in a stable form for decades if not centuries, with the added benefit of the immobilisation of heavy metals (Heilmann et al., 2010; Sayre, 2010) and opportunities for mine site rehabilitation. Such a product could be co-produced with other high-value products to ensure economic feasibility.

Emissions Reduction Fund (ERF) ACCU method opportunities

To access carbon markets, a microalgae-based entity would need to register a method with the ERF to receive an ACCU for each metric ton of CO_2-e either permanently stored in a (a) product or (b) prevented through the displacement of fossil fuel combustion. Both carbon abatement approaches have been considered.

Permanent carbon storage

Sequestered carbon must be stored for at least 25 years to be considered as permanent carbon abatement (Carbon Farming Initiative Act 2011 (Australian Government, 2011)). This requirement would prevent Australia's Clean Energy Regulator (CER) issuing ACCUs for carbon captured in many microalgae-derived products such as animal feeds, biofertilisers, biostimulants, biodegradable bioplastics, biofuels, essential oils, and pigments.

Opportunities may be present to propose and develop a CER registrable method for obtaining ACCUs from downstream products of microalgae processing that capture carbon for more than 25 years. Until technologies are commercialised for processing biomass into cost-competitive non-degradable plastics, graphite, or construction materials, activated carbon represents the most likely target product that can satisfy CER permanency requirements.

The Australian Government's *Department of Climate Change, Energy, the Environment and Water* (DCCEEW) currently has no methods available for crediting ACCUs for the processing of biomass to achieve permanent carbon abatement (Personal communication by email from the Department of Climate Change, Energy, the Environment and Water (DCCEEW), 18th March 2024). It indicated, however, that a framework exists for the proposal of such methods.

Fossil fuel displacement

The processing of harvested biomass into renewable fuels would provide access to proposed microalgae cultivation system's opportunity to access the ERF is limited to its *Industrial and Commercial Emissions Reduction* (ICER) Method (Australian Government Clean Energy Regulator, 2021). The ICER provides a mechanism for issuing ACCUs to activities that reduce "energy emissions (emissions from the combustion of fuel and consumption of electricity) and industrial process emissions produced by existing emissions-producing equipment."[1] The downstream processing of microalgae to produce biofuels for use in existing emissions-producing equipment represents an eligible activity for generating ACCUs or Safeguard Mechanism Credits (SMC; see below) within this method.

[1] The CER's *Carbon Credits (Carbon Farming Initiative— Facilities) Methodology Determination 2015* (Australian Government Department of Climate Change, Energy, the Environment and Water, 2016) provides a similar method. Projects previously registered under this method can transfer to the ICER.

The implications of the Safeguard Mechanism on product prices

Australia's Safeguard Mechanism legislation was enacted to reduce carbon emissions at industrial facilities that produce more than 100,000 metric tons of CO_2-e per year, defined as Safeguard Mechanism Facility (SMF). The legislation obliges an SMF to reduce its historical baseline emissions or offset its emissions (highest level of emissions for a specific period) 4.9% per year until 2030 (Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW), 2024). If an SMF cannot achieve its required emissions reduction, it can offset these by purchasing ACCUs from the Government at a fixed price of AU$75 plus Consumer Price Index (CPI), increasing with CPI plus 2% each year from 2023/2024.

An SMF can apply for Safeguard Mechanism Credit Units (SMCs) when their emissions are below their baseline in a particular financial year or below the net baseline at the end of a multi-year monitoring period (Australian Government Clean Energy Regulator, 2024b). As for ACCUs, each SMC represents one metric ton of CO_2-e. An SMF may choose to sell SMCs to other SMF, surrender them to stay within their baseline requirements, or retain them for future use until 2030. An SMF will accrue SMCs rather than ACCUs when it uses renewable fuels to reduce emissions below its required baseline.

To enforce the Safeguard Mechanism obligations, a SMF is penalised AU$275 per metric ton of excess emissions each year, "charged at one-third of the maximum civil penalty to a maximum of 150,000 penalty units" (Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW), 2024). Though the Government says it is confident there will be sufficient ACCUs and SMCs available at this price through to 2035, it remains possible that the industry could either become excluded from accessing ACCUs or that there simply will not be sufficient credits available. If this were to occur, the use of microalgae biomass to offset or reduce emissions is worth up to AU$275 per metric ton of CO_2-e abatement.

4.4 Business case for innovation and development of the most promising algae-based technologies

A business case for the establishment of algae production within the context of Australian mining sites will consist of many economic, environmental and social aspects, which are heavily dependent on location, site, strain, cultivation technology, scale and end-product(s). In these early exploratory phases, establishing a full business case is unfeasible, however some general extrapolations of the most feasible options can be made based on the outputs of this report. In this chapter, the possible project objectives, approaches and business opportunities are briefly described, and crucial questions that need to be answered to establish the full business case are identified.

4.4.1 Problem definition

Mining operations pose substantial environmental challenges. Operations may generate mine water of a quality that prevents its use for agricultural purposes or poses an environmental threat to local water sources. Depending on the extraction method used, mineral targeted, and local geology, the produced water may contain concentrated salts, heavy metals, acids, and other pollutants. Additionally, mining can lead to the degradation of landscapes and ecosystems, disrupting natural habitats. The industry also contributes to elevated CO_2 emissions and associated effects on climate change. Furthermore, the environmental damage and future loss of livelihood opportunities associated with inevitable mine closures can have serious socioeconomic consequences for local and First Nations communities. These environmental as well as socioeconomic issues require attention, during operation, but also post mine closure.

Within Queensland alone, the Government estimated that rehabilitating the states mines will cost more than AU$10 billion (Queensland Treasury, 2021). Until recently, the rehabilitation process was not viewed as an opportunity to achieve post-mining economic objectives. Mine rehabilitation was largely regarded as an obligation to rectify environmental disturbance, with governments and mining companies placing an almost singular emphasis on defining and meeting *environmental* completion criteria (Everingham *et al*., 2018). But given mine closure invariably involves the ongoing human and economic occupation of former mine sites (Harvey, 2016), a narrow focus on achieving environmental outcomes inadvertently threatens to diminish the economic and social fabric of post-mining regional communities. New algal technology solutions represent an opportunity to leverage the rehabilitation process to achieve economic activity and social outcomes that continue beyond mine closure in addition to environmental benefits.

A range of problems for which algae technologies could provide potential solutions are listed in Table 16.

Table 16: Overview of rehabilitation concerns in mining contexts

Rehabilitation problem	Description
Saline water-filled voids	Open-cut mining operations create final deep voids that gradually fill via rainfall capture and the ingress of naturally saline groundwater. Unless sustainable desalination methods are developed, voids may gradually increase in salinity due to evaporative water losses combined with the continuing ingress of saline ground water. The authorisation to retain final voids is not expected to apply to future mining approvals. Some mines have restrictions on the area of final voids, and this may oblige these operations to partially backfill these pits unless their retention can be demonstrated to be in the public interest.
Tailings dams	Containing waste materials after the washing and processing of extracted minerals and metals, tailings dams present problems such as potential contamination with toxic materials and metals; instability caused by the presence of fine, chemically reactive materials; a lack of soil quality and structure for supporting vegetation establishment.
Brine ponds	The use of reverse osmosis to treat mine water especially during the dewatering of underground mines produces brine. Brine is either pumped into existing water filled voids, thereby exacerbating salinity challenges or evaporated in expensive brine ponds. The industry lacks a sustainable solution for brine management.
Sloped fragile landforms	Open-cut mining methods produce spoil dumps that mining operations attempt to reshape into sustainable sloped landforms. The establishment of vegetative groundcover on these fragile slopes is critical to the achievement of stable rehabilitated landforms. Many open-cut mines report that this outcome is often challenged by a significant topsoil deficit relative to rehabilitation requirements.

4.4.2 Solutions to problems

Algae-based technologies have the potential to provide innovative and sustainable solutions for the mining industries. They enable effective CO_2 sequestration by capturing and storing carbon dioxide, can be used for the treatment of contaminated waters from mining operations and to produce products that could be used within mining-rehabilitation contexts (e.g., biofertiliser and biochar). Furthermore, algae-based processes facilitate the creation of other products, such as biofuels, bioplastics, derived from harvested algal biomass, which could lead to additional revenue generation.

4.4.3 Approaches to implement solutions

Implementation of the algae within a mining context will involve various phases, starting with site selection and definition of the site-specific objectives. This will then help to identify the most feasible technologies that could be implemented, and subsequent due diligence will determine economic, social and environmental opportunities as well as risks. Figure 31 shows a proposed flow-chart detailing the 8 anticipated phases needed for full project realisation.

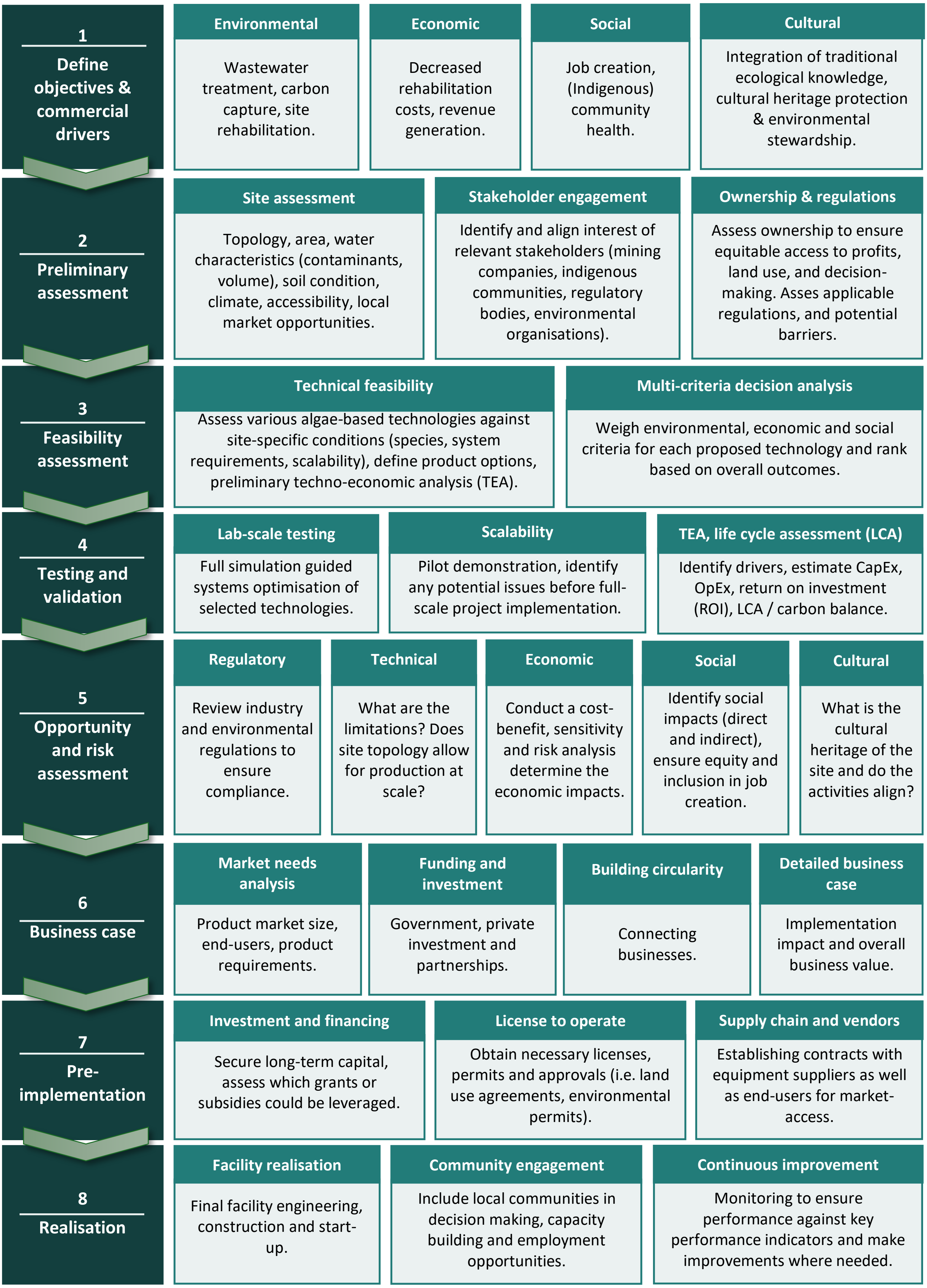


Figure 31: Flow-chart for anticipated phases moving towards full project realisation of algal technologies.

4.4.4 Risks associated with solutions versus not doing anything

When developing and implementing algae technologies in mining contexts, several risks need to be considered. Evaluating how these risks compare to the benefits, as well as to the risks associated with alternatives or inaction, is crucial in assessing the project's impact and feasibility. Initially, the risks of implementing algae-based solutions include technical challenges related to scaling up algae cultivation and processing, which could hinder project success. These challenges are compounded by the high capital investment required for research and development, infrastructure, and potential uncertainty regarding regulatory approvals and market acceptance.

On the other hand, the risks of inaction are significant. Continued environmental degradation, water and soil contamination, persistent CO_2 emissions contributing to climate change, and loss of biodiversity and ecosystem degradation are notable concerns. Besides obvious environmental concerns, additionally, failing to act could have significant associated financial risks (e.g., fines), as well as negative socioeconomic impacts on local and First Nations communities. All in all, these could lead to legal and reputational risks for mining companies due to environmental non-compliance and community conflicts. As the specifics of a project are defined, these risks will become clearer, thereby supporting the business case for implementing algae technologies in mining contexts.

In Figure 32 an overview is provided of the anticipated risks associated with implementation of algae-based solutions in mining environments, as well as the risks of inaction. Ultimately, while implementing algae-based solutions carries risks, inaction poses significant environmental, financial, legal, and social risks, making the case for pursuing innovative algae technologies in mining contexts.

Implementing algae-based solutions	Risks	Inaction
Scaling up algae cultivation and processing could face technical difficulties such as controlling environmental factors (e.g., water quality, temperature) and maintaining consistent yields.	**Technical**	Missed opportunity to trial innovative technology targeted toward mine-site and wastewater remediation and intellectual property (IP) development.
High capital investments for infrastructure, research, and development, as well as operational costs, may lead to financial risks, especially if market acceptance or revenue generation is delayed.	**Financial**	Mining companies may face fines for non-compliance with environmental regulations and incur costs related to environmental degradation, rehabilitation, or carbon pricing mechanisms.
Mismanagement of algae cultivation could lead to unintended human, animal or environmental health impacts, such as short term cyanotoxin exposure, invasive species or nutrient imbalances.	**Health, safety and environment**	Continued degradation, including water and soil contamination, CO_2 emissions, and biodiversity loss, would lead to long-term human, animal and ecosystem harm.
Uncertainty in obtaining regulatory approvals for the integration of algae-based technologies with mining operations may delay project implementation and increase compliance costs.	**Policy and regulation**	Failure to comply with evolving regulations on emissions and environmental protection could lead to penalties and legal liabilities.
Projects may face challenges if not properly aligned with land rights agreements and revenue-sharing models with Indigenous communities, potentially leading to community conflicts.	**Traditional Owners**	Inaction could result in reputational damage and strained relationships with Indigenous communities due to unaddressed land rights, cultural concerns, and missed revenue-sharing opportunities.

Figure 32: Risks of action vs. risks of inaction across technical, financial, environmental, regulatory and indigenous rights categories.

4.4.5 Potential business value created from solutions

As identified in Chapter 4.1, there are notable environmental, economic and social benefits which could potentially result from the application of algae within mining contexts. Focussing on the specific business value that could potentially be generated, this will be highly dependent on mine site, strain, cultivation method and other process and product considerations. The possible product portfolio as shown in Chapter 4.3 is large, ranging from high volume-low value biofuels to high-value bioproducts with significantly smaller markets and higher production costs. The economic business value that could be generated can be estimated in three phases: Primarily it could be driven by revenue generation from produced products, where production costs and the product price will be the main drivers. Secondly, with the proper process and product considerations, and based on the life cycle assessment of the process, carbon credits can be generated for the process that can be sold in carbon markets or used to offset the company's emissions, potentially leading to cost savings. Finally, costs savings on rehabilitation could also be significant, depending on mine site location and existing rehabilitation plans. Further project specification and development would be needed to accurately quantify the potential business values of various process options.

4.4.6 Economic opportunities for local (including First Nations) communities

Algae-based projects within mining contexts can create significant socioeconomic opportunities by generating employment in algae farming, bioreactor maintenance, and product processing. These initiatives offer the potential for training programs that build local expertise in algae technologies, contributing to workforce development. Early engagement with local and First Nations communities is critical, ensuring that these stakeholders are involved from the beginning. This helps build trust and fosters transparency. Establishing good processes through regular dialogue, co-designing the project alongside the community, and respecting traditional ecological knowledge are essential for ensuring cultural appropriateness and project success.

Collaborative efforts, such as revenue-sharing models, can ensure mutual benefits, with local and First Nations communities receiving a share of the financial returns from algae production. This not only boosts local economies but also builds long-term partnerships. By incorporating these elements into algae-based projects, companies can foster stronger relationships with Indigenous groups, ensuring that both economic and cultural objectives are met.

4.4.7 Potential paths to market

To ensure the successful commercialisation of algae-based products from mining contexts, a comprehensive path to market is required, incorporating research, product development, partnerships, compliance, and marketing efforts.

1. Through **Market Research and Analysis** conduct thorough research to identify industry demand for algae-based products and potential customers. This could include sectors such as biofuels, agriculture, or plastics manufacturing. Understanding market trends, regional markets, competitors, and potential demand will allow for better-targeted products and strategies that address specific industry needs and opportunities.
2. With **Product Development and Testing**, develop the algae-based products to meet industry standards and customer expectations. Rigorous testing will be essential to ensure the products meet performance requirements, are scalable, and comply with necessary industry regulations. Testing also ensures that products meet environmental and safety standards, essential for building trust and credibility in the market.
3. **Commercial Partnerships** will play a crucial role in facilitating market entry. Forming strategic alliances with established companies in target industries can accelerate product distribution and provide access to established networks and infrastructure. Partnerships in biofuel, agriculture, or manufacturing can enhance market penetration and help overcome initial barriers to entry.
4. **Regulatory Compliance** is another key factor. Ensuring that algae-based products comply with relevant environmental, health, and safety regulations is crucial for obtaining necessary certifications and licenses to operate in various industries, such as agriculture and biofuels.
5. Finally, **Marketing and Sales** efforts should focus on promoting the environmental and economic benefits of the algae-based products. Effective marketing strategies highlight the sustainable advantages of the products, targeting eco-conscious customers and industries seeking greener alternatives. Building sales channels, including direct sales, online platforms, and partnerships, will facilitate broader market reach and consumer engagement.

This integrated approach can ensure that algae-based products can successfully reach and thrive in various markets, supported by research, strong partnerships, and regulatory compliance.

Business Case Summary

As we conclude this chapter on business case development, it is important to note that each mining site will have different requirements, environmental conditions, and objectives, and hence will need a tailored business case. At this stage, developing a detailed business case is not feasible due to the many unanswered questions related to site-specific factors, available resources, and regulatory considerations. However, the key questions outlined here will provide essential guidelines for what must be understood to form a solid business case:

1. Define Project Scope and Objectives

- What are the primary objectives of algae cultivation at the mining site? (e.g., CO_2 sequestration, wastewater treatment, biomass production for biofuels, etc.)
- Is the project aimed at post-mine rehabilitation, ongoing operational support, or both?
- Are there specific sustainability goals or regulatory requirements that the project needs to meet?

2. Site and Resource Availability

- What is the location and size of the mining site where algae cultivation is proposed?
- What resources are available at the site that could support algae cultivation? (e.g., CO_2 source, mine water and other water sources, land area, sunlight, renewable energy (electricity))
- Are there any constraints or limitations at the site (e.g., climate, infrastructure, proximity to markets)?

3. Technology

- What algae cultivation technologies are being considered? (e.g., open ponds, photobioreactors, floating bioreactors)
- What integration is being planned with other processes at the mining site or nearby industries (e.g., using mine wastewater, capturing flue gases)?

4. Market Analysis

- What are the target markets for the algae products? (e.g., biofertilisers, biofuels, bioplastics, nutraceuticals, animal feed)
- What is the estimated demand for these products in Australia and globally?
- Who are the potential customers or end-users, and what are their purchasing criteria?

5. Financial Projections

- What are the initial capital expenditures (CapEx) and ongoing operational expenditures (OpEx) for the project?
- What revenue streams are expected from the sale of algae-derived products?
- What potential financial incentives or subsidies for sustainable or renewable energy projects in Australia are available and could be applicable?

- What potential financial credits (such as wastewater treatment credit, carbon credit) could be applicable?

6. Regulatory and Compliance Considerations

- What are the regulatory requirements for algae cultivation and product sales in Australia?
- Are there specific environmental or safety regulations that must be adhered to?
- Is the project eligible for carbon credits or other environmental certifications?

7. Risks and Mitigation Strategies

- What are the main risks associated with the project (e.g., technical, financial, market)?
- How do you plan to mitigate these risks?
- What are the risks of not implementing the algae cultivation project, particularly in terms of environmental impact or regulatory compliance?

8. Social and Community Impact

- How will the project benefit local communities, including First Nations communities?
- Are there opportunities for local job creation or partnerships with local businesses?
- What are the potential social risks, and how will they be addressed?

9. Sustainability and Environmental Impact

- How will algae cultivation contribute to the sustainability goals of the mining operation?
- What are the expected environmental benefits (e.g., reduction in carbon footprint, water treatment)?
- How will the project be monitored and reported in terms of environmental performance?

10. Strategic Partnerships and Collaboration

- Are there opportunities for collaboration with research institutions, government bodies, or other industries?
- How will partnerships enhance the project’s viability and success?
- What are the potential synergies with other industries (e.g., agriculture, aquaculture)?

11. Pathways to Market

- How will the algae products be processed and brought to market?
- What distribution channels and logistics are required?
- What is the go-to-market strategy for different product lines?

12. Long-term Vision and Scalability

- What is the long-term vision for algae cultivation at the site?
- Are there plans for scaling the project to other sites or increasing production capacity?
- How will the project evolve in response to market changes or technological advancements?

5. Research gaps and opportunities for potential Stage 2 project scope

5.1 Research gaps

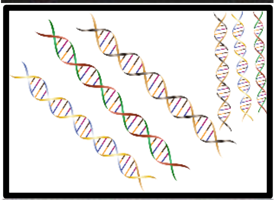
Based on the Stage 1 review and stakeholder engagement, several research gaps have been identified as described below.

1. **Strain selection and cultivation optimisation**: In general, only a few algal species have been cultivated for mass production and the algae culture field has not yet developed as much as agriculture. More research is needed to identify and optimise algae strains that are particularly effective at thriving in the (waste) waters associated with mining sites. These are characterised by elevated levels of heavy metals and other contaminants, as well as varying pH and salinities, all of which can significantly impact algae growth.
2. **Product development and application**: There is a need to expand research into the specific applications of algae-derived products in the mining context. For products such as biochar or algae-based dust suppressants, understanding the long-term impacts and effectiveness of these applications in real-world scenarios will be critical for broader adoption. Furthermore, for products targeted for food, feed or nutraceutical use, the implications of contaminants on the product quality need to be investigated to ensure product quality and safety.
3. **Process development:** Based on choices of mine site, strain and product, process design and development will be a crucial aspect in being able to define optimal production conditions. Furthermore, co-production of multiple products to generate multiple income streams will also be an important aspect to increase value, and production at scale (pilot) and modelling will be important to determine facility and production costs needed to drive further development.
4. **Environmental impact assessment**: Comprehensive studies are needed to evaluate the environmental impacts of large-scale algae cultivation at mining sites, including potential risks of introducing non-native species, nutrient runoff, and the ecological balance of rehabilitated sites.
5. **Costs, revenue and economic viability**: Research into the economic models that can support the integration of algae cultivation within mining operations is essential. This includes assessing market demand, production costs, and the potential for generating revenue through carbon credits and products, as well as assessing the economic benefits of implementing the solution and the economic risks associated with not implementing such solutions.
6. **Regulatory frameworks**: Understanding applicable government, industry and societal regulations for implementing algae on mine sites will be crucial to support industry to identify regulatory barriers and opportunities.

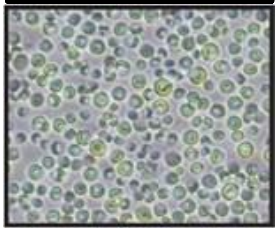
5.2 Opportunities for potential Stage 2 project scope

Based on the Stage 1 review and stakeholder engagement, several opportunities and potential activities have been identified for the scope of a potential Stage 2 project as detailed below.

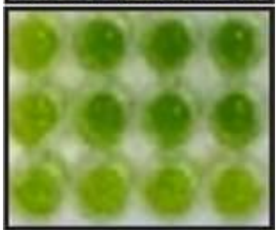
Characterisation of mine water samples: Water samples from mine sites can be characterised for various water quality parameters (e.g., pH, elemental analysis, electric conductivity) and evaluated together with other mine site characteristics (e.g., location, volume, surface area) to identify promising sites for the collection of water for microalgal bioprospecting and exploration of algal technologies.



Metagenomic analysis of algae at mine sites: Water samples from mine sites can be sampled using strategies that maximise microalgae diversity and recovery. Metagenomics can be used to identify native microalgae in mine water samples to guide the selection of strains from algal culture collections.



Microalgae isolation and identification: Microalgal strains can be isolated from mine water samples and identified based on deoxyribonucleic acid (DNA) sequencing to generate a strain collection. The identity of the algae can be linked to associated mine-water properties to use as resource for exploring various mine site applications.



High-throughput growth optimisation: Using a unique high-throughput microalgae growth optimisation robot, growth parameters can be optimised for isolated strains to identify the best microalgae production conditions for scale up. Focus can be e.g., on target conditions and contaminants present in selected mine waters (e.g., specific heavy metals, acidic, saline).

Direct microalgal contaminant removal from mine water: Apply simulation-guided systems optimisation to model complex interactions between environmental variables at mine sites and selected algae strains. Selected algal strains can be cultivated in mine water, and the removal of targeted contaminants such as heavy metals or salts optimised.

Indirect biotechnical mine water treatment with microalgal biomass: The treatment of mine water using bioprocesses that utilise algal biomass as a carbon and electron source can be explored with laboratory-scale bioreactors. The performance of the process(es) for removing oxyanions (e.g., sulfate, nitrate, selenate) and metals can be evaluated under various operating conditions for process optimisation.

Mine waste stabilisation with algal biomass: The stabilisation of selected acid generating mine wastes with algal biomass can be explored using laboratory-scale microcosm or column studies. The performance of the application can be evaluated based on the ability of the algal biomass to suppress AMD formation.

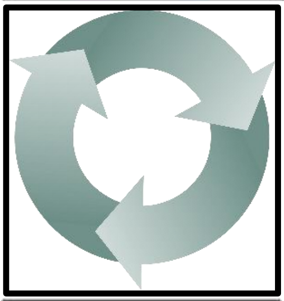
Dust suppression with algal biomass: The potential to use algal biomass or algae-based products to suppress dust at mine sites can be explored using laboratory-scale wind-tunnel experiments with mine site soil samples. The performance of the algal amendments can be compared against commercially available dust suppressants.

Mine site rehabilitation with algal biomass: The potential to use algal biomass as a fertiliser and biostimulant in mine site rehabilitation can be explored using laboratory- and bench-scale studies. The evaluation can include e.g., the amendment of soil and/or mine waste from selected mine sites, and determination of the effect of algal biomass on seed germination and plant growth.

Bioeconomic survey and product option analysis: The composition of the biomass of algal strains isolated from mine sites can be analysed to explore options for value generation, either as whole biomass, or biorefined products (e.g., aquafeeds, biofertilisers, proteins, omega-3 rich oils, pigments, biochar, and renewable fuel).

Process design and techno-economics: Based on the algal strain choices and potential mine site topology, the best options (e.g., raceway ponds, (floating) photobioreactors for algae cultivation at selected mine sites can be determined. A techno-economics assessment and sensitivity analysis can be performed to determine production costs for various options, including multiple-product biorefinery options.

Nutrient waste stream inventory: Industries near mine sites can be identified for potential supply of other waste streams rich in nutrients and CO_2 to support algae growth, and industrial ecology in which the waste from one industry becomes a feedstock for another.



Life cycle assessment for selected algal technologies: Life cycle assessments can be performed for selected algal technologies, e.g., focusing on carbon, and linking to potential financial benefits resulting from generated carbon credit units.

Regulatory constraints: A database of relevant regulatory frameworks can be scoped and generated, and their potential constraint for commercialisation pathways assessed, including possible limitations for cultivation at mine sites, but also product quality and regulatory requirements, water use limitations, and occupational health and safety.

Engagement with First Nations communities: While building trust and strengthening relationships between the CRCTiME project and First Nations communities, the ideas on integrating algae-based technologies for improved environmental outcomes and sustainable post-mining futures can be respectfully presented to traditional owners. Moreover, it can be established what good economic, social, and environmental outcomes would look like and what the preferred local microalgae projects might be as well as what is to be avoided. Moreover, steps can be taken to ensure benefit sharing is agreed, captured and reflected for the community.

Identification of pilot-scale test work opportunities:

Based on the Stage 1 and 2 outcomes, potential site(s) and technology(ies) can be identified for pilot-scale demonstration test work. The identification can be done in consultation with industry partners. Moreover, opportunities can be identified for engaging with local communities near the potential pilot-scale demonstration sites.

The most promising opportunities for potential Stage 2 project scope will be further discussed and developed in consultation with industry and government stakeholders and CRC TiME to refine the Stage 2 proposal.

6. Conclusions

This report covers a review of algae-based technologies that help to mitigate the environmental impacts of mining during operations and after closure and to enable the creation of algae-based supply chains. Based on the literature review and stakeholder engagement conducted as part of the Stage 1 of this project, several conclusions can be drawn as outlined below.

Mine site environmental challenges

- Environmental challenges at mine sites include physical disturbance of land, energy consumption and air emissions, the generation of mining and metallurgical wastes, and mine water. Moreover, the loss of valuable land and water assets can notably impact the long-term sustainability of local communities.
- Mine water pH can vary from acidic to alkaline, with differences in the concentrations of sulfate, metals, and metalloids across different types of mines.

Benefits from algal technologies at mine sites

- Integrating algae into mining scenarios offers significant benefits by combining ecological restoration with economic value generation.
- Algae cultivation can treat mine water and sequester carbon dioxide, and algal biomass supports mine waste stabilisation and dust suppression and improves plant growth when used as fertiliser and biostimulant. Thus, the application of algae at mine sites accelerates ecological recovery while reducing environmental impacts, such as pollutant levels and greenhouse gas emissions.
- Moreover, algal biomass can be used as a raw material to produce bioplastics, biofuels, pigments and animal feeds. Algal cultivation may also be complementary to other water uses for mutual benefits, such as aquaculture which may use algae as feed and provide nutrients for algal cultivation. Hence, algae-based technologies create sustainable business opportunities, turning post-mining land into economically productive ecosystems.
- This dual approach not only enhances rehabilitation outcomes but also ensures long-term sustainability for mining sites through the development of business opportunities for ongoing value generation beyond mine closure. Algal cultivation at mine sites may create jobs and offer opportunities to engage Traditional Owners and other local communities.

Selection of algal species and cultivation, harvesting and processing technologies

- Various micro- and macroalgae have been detected and identified in mine waters, indicating that their cultivation at mine sites should be possible if suitable growth conditions are provided.
- Algal growth requires sunlight and essential macro- and micronutrients.
- Depending on mine water quality, pre-treatment of mine water may be required to adjust pH, to remove toxic elements, suspended solids, sulfate or salts, and/or to add nutrients to support algal growth.
- The selection process of algal species and cultivation systems for implementation in mine sites can include 1) reviewing mine site characteristics and aim for algal processes, 2) the selection of algal species based on their growth rate and suitability to the mine site conditions and application, 3) identifying possible mine water treatment or amendment needs, 4) the selection of algal cultivation systems, 5) the selection of algal harvesting and processing systems, 6) the verification of algal end-products in terms of yield, quality and suitability of biomass residue for other applications, and the market price of the products and 7) the optimisation of the process.
- The growth rate of algae is a key factor influencing the time required for scaling up algal cultivation.
- Large-scale microalgal cultivation can be carried out in open raceway ponds, closed photobioreactors, floating photobioreactors or biofilm-based algal turf scrubbers. Macro-algal

cultivation systems can utilise free-floating algae, or biomass adhered to the bottom of the water body or solid substratum, e.g., using rope or raft systems.

- Microalgal harvesting methods include centrifugation, tangential flow filtration, forward osmosis, flocculation, bioflocculation, dissolved air flotation, electroflotation and magnetic separation. Macroalgal harvesting can be conducted either manually with cutting tools or through mechanical harvesting using amphibious vehicles, boats, land-based long-armed vehicles equipped with suction apparatus, rotating mowers, cutters, rotating blades and dredgers.
- Whole algae biomass can be used as is for several applications (e.g., feeds supplements, fertilisers), however, cell rupture is required for the extraction of some valuable components (e.g., oils, proteins, pigments). Cell disruption can be carried out through mechanical, chemical, enzymatic, thermal, electrical or other emerging technologies.

Regulatory and other constraints for the application of algal technologies

- Regulatory requirements that need to be considered if planning algal cultivation and use at mine sites include 1) land use agreements (e.g., Indigenous land use agreements and mining lease commercial conditions), 2) environmental permits and compliance (e.g., water use license, waste management and rehabilitation requirements), 3) health and safety standards for occupational, algal process and product safety, and 4) biodiversity and ecosystem protection (e.g., non-invasive species and ecosystem monitoring).
- Mine rehabilitation guidelines provide a framework for the systematic recovery of ecosystems, including the stabilisation of mine waste, restoration of vegetation, and improvement of water quality.
- The assembly of a regulation database, consisting of government, industry and societal regulations that impact algae biomass production, processing and products specifically at mine sites could support industry to identify regulatory barriers and opportunities.

Business case for the application of algal technologies at mine sites

- The application of algal technologies at mine sites offers significant economic, social, and environmental benefits, all of which can be quantified through various metrics.
- Estimates of algal production cost vary with various growth systems and geographic locations, typically being in the order of 10-100 AU$ kg^{-1} of dry algal biomass.
- The global algae markets are rapidly increasing with a value of US$1.9-5.3 billion in 2023 and estimated annual growth of approximately 5-6%. The market size and value of algal products vary widely depending on the application.
- For bulk algae products to become cost competitive, multi-product biorefineries will allow compensation of current production costs to achieve profitability. Additionally, algae production costs can be reduced through technical refinement, policy optimisation and scale.
- Algal cultivation can enable industrial ecology and symbiotic relationships with nearby industries, where CO_2 emissions and nutrient rich wastewater streams from these industries can support algal growth while the algae purify the exhaust gases and wastewater.
- A business case for the establishment of algae production within the context of Australian mining sites will consist of many economic, environmental and social aspects, which are heavily dependent on location, site, algae strain, cultivation technology and end-product(s).
- The implementation of the algae within a mining context will involve various phases, starting with site selection and definition of the site-specific objective, which will inform the selection of the most feasible technologies that could be implemented, followed by due diligence to determine economic, social and environmental opportunities as well as risks.
- To ensure the successful commercialisation of algae-based products from mining contexts, a comprehensive path to market is required, incorporating market research and analysis, product development and testing, commercial partnerships, regulatory compliance, and marketing efforts.

- Key considerations for a solid business case for algal technologies include: 1) defining project scope and objectives, 2) site and resource availability, 3) technologies, 4) market analysis, 5) financial projections, 6) regulatory and compliance considerations, 7) risks and mitigation strategies, 8) social and community impacts, 9) sustainability and environmental impacts, 10) strategic partnerships and collaboration, 11) pathways to market, and 12) long-term vision and scalability.

Knowledge gaps and opportunities for potential Stage 2 project scope

- A few examples of research gaps for mine site algal technologies include: 1) strain selection and cultivation optimisation for mine water conditions, 2) product development for various applications, 3) process development, 4) environmental impact assessment, 5) cost, revenue and economic viability assessment, and 6) increasing the understanding on regulatory frameworks.
- Based on the research gaps, opportunities for the potential Stage 2 project scope include the characterisation of mine water samples, metagenomic analysis of algae at mine sites, the isolation of algal strains from mine water, and the high throughput growth optimisation of algal strains. Moreover, the use of algal biomass for direct or indirect mine water treatment, mine waste stabilisation, dust suppression and mine site rehabilitation can be explored. Further study could also include a bioeconomic survey and product option analysis, process design and techno-economic analysis, nutrient waste stream inventory, life cycle assessment of selected algal technologies, development of a database on regulatory constraints, engagement with First Nations communities and identification of opportunities for possible pilot-scale test work.

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8. References

Abinandan, S., Perera, I. A., Subashchandrabose, S. R., Venkateswarlu, K., Cole, N. & Megharaj, M. (2020). Acid-adapted microalgae exhibit phenotypic changes for their survival in acid mine drainage samples. FEMS Microbiology Ecology 96(11), fiaa113. https://doi.org/10.1093/femsec/fiaa113

Abinandan, S., Subashchandrabose, S. R., Cole, N., Dharmarajan, R., Venkateswarlu, K. & Megharaj, M. (2019). Sustainable production of biomass and biodiesel by acclimation of non-acidophilic microalgae to acidic conditions. Bioresource Technology 271, 316–324. https://doi.org/10.1016/j.biortech.2018.09.140

Abinandan, S., Subashchandrabose, S. R., Venkateswarlu, K. & Megharaj, M. (2018). Microalgae-bacteria biofilms: A sustainable synergistic approach in remediation of acid mine drainage. Applied Microbiology and Biotechnology 102(3), 1131–1144. https://doi.org/10.1007/s00253-017-8693-7

Abiusi, F., Trompetter, E., Pollio, A., Wijffels, R. H. & Janssen, M. (2022). Acid tolerant and acidophilic microalgae: An underexplored world of biotechnological opportunities. Frontiers in Microbiology 13, 820907. https://doi.org/10.3389/fmicb.2022.820907

Acién, F. G., Fernández, J. M., Magán, J. J., and Molina, E. (2012). Production cost of a real microalgae production plant and strategies to reduce it. Biotechnology Advances 30(6), 1344–53. https://doi.org/10.1016/j.biotechadv.2012.02.005

Adams, T. (2022). 6 Dust Control Market Trends to Look out for in 2022. GRT. February 7, 2022. https://globalroadtechnology.com/6-dust-control-market-trends-2022/

Adarme-Vega, T. C., Lim, D. K. Y., Timmins, M., Vernen, F., Li, Y. &Schenk, P. M. (2012). Microalgal biofactories: a promising approach towards sustainable omega-3 fatty acid production. Microbial Cell Factories 11, 96. https://doi.org/10.1186/1475-2859-11-96

Adeel, M., Zain, M., Shakoor, N., Ahmad, M. A., Azeem, I., Aziz, M. A., Tulcan, R. X. S., Rathore, A., Tahir, M., Horton, R., Xu, M. & Yukui, R. (2023). Global navigation of lithium in water bodies and emerging human health crisis. npj Clean Water 6, 33. https://doi.org/10.1038/s41545-023-00238-w

Adey, W. H., Kangas, P. C., & Mulbry, W. (2011). Algal turf scrubbing: cleaning surface waters with solar energy while producing a biofuel. Bioscience 61(6), 434-441. https://doi.org/10.1525/bio.2011.61.6.5

Adey, W. H., Laughinghouse, H. D., IV, Miller, J. B., Hayek, L. A. C., Thompson, J. G., Bertman, S., Hampel, K. & Puvanendran, S. (2013). Algal turf scrubber (ATS) floways on the Great Wicomico River, Chesapeake Bay: productivity, algal community structure, substrate and chemistry. Journal of Phycology 49, 489-501. https://doi.org/10.1111/jpy.12056

Adhikari, J., Pang, G., Morisada, S., Kawakita, H., Ohto, K., Inoue, K., Demura, M., Maeda, S. & Nakamizo, K. (2024). Defatted microalgae *Haematococcus pluvialis*: A sustainable source for gold recovery. Journal of Environmental Chemical Engineering,12(5), 113804. https://doi.org/10.1016/j.jece.2024.113804

Adhikari, J., Sakamura, R., Kawakita, H., Morisada, S., Ohto, K., Inoue, K. & Demura, M. (2023). Au(iii) recovery using two microalgal adsorbents with or without treatment with concentrated sulfuric acid. Journal of Water Process Engineering 56, 104520. https://doi.org/10.1016/j.jwpe.2023.104520

Alam, S. N., Khalid, Z., Guldhe, A., Singh, B. & Korstad, J. (2021). Harvesting and pretreatment techniques of aquatic macrophytes and macroalgae for production of biofuels. Environmental Sustainability 4, 299–316. https://doi.org/10.1007/s42398-021-00178-6.

Alavianghavanini, A., Moheimani, N. R. & Bahri, P. A. (2024). Producing protein-based products from microalgae cultivated on anaerobically digested abattoir effluent: Process integration and techno-economic analysis. Bioresource Technology Reports 25, 101734. https://doi.org/10.1016/j.biteb.2023.101734

Al-Jabri, H., Das, P., Khan, S., Thaher, M. & AbdulQuadir, M. (2021). Treatment of wastewaters by microalgae and the potential applications of the produced biomass-A review. Water 13(1), 27. https://doi.org/10.3390/w13010027

Al-Mardeai, S., El-Hassan, H., Moheimani, N., Hamza, W., El-Maaddawy, T. & Al-Zuhair, S. (2024). Optimization of microalgal $CaCO_3$ production with aim to produce biocement. Chemical Engineering Research and Design 208, 515–525. https://doi.org/10.1016/j.cherd.2024.07.020

Almomani, F. & Bhosale, R. R. (2021). Bio-sorption of toxic metals from industrial wastewater by algae strains *Spirulina platensis* and *Chlorella vulgaris*: application of isotherm, kinetic models and process optimization. Science of the Total Environment 755, 142654. https://doi.org/10.1016/j.scitotenv.2020.142654

Alquethamy, S. F., Adams, F. G., Maharjan, R., Delgado, N. N., Zang, M., Ganio, K., Paton, J. C., Hassan, K. A., Paulsen, I. T., McDevitt, C. A., Cain, A. K., Eijkelkamp, B. A. & Kelly, R. M. (2021). The molecular basis of *Acinetobacter baumannii* cadmium toxicity and resistance. Applied and Environmental Microbiology 87(22), e0171821. https://doi.org/10.1128/AEM.01718-21

Al-Shwafi, N. A. & Rushdi, A. I. (2008). Heavy metal concentrations in marine green brown, and red seaweeds from coastal waters of Yemen, the Gulf of Aden. Environmental Geology 55, 653e660. https://doi.org/10.1007/s00254-007-1015-0

Amaral-Zettler, L. A. (2012). Eukaryotic diversity at pH extremes. Frontiers in Microbiology 3, 441, 1-17. https://doi.org/10.3389/fmicb.2012.00441

Andrade, S., Medina, M. H., Moffett, J. W. & Correa, J. A. (2006). Cadmium− copper antagonism in seaweeds inhabiting coastal areas affected by copper mine waste disposals. Environmental Science & Technology 40(14), 4382-4387. https://pubs.acs.org/doi/10.1021/es060278c

Antonelli, P. M., Fraser, L. H., Gardner, W. C., Broersma, K., Karakatsoulis, J. & Phillips, M. E. (2018) Long term carbon sequestration potential of biosolid-amended copper and molybdenum mine tailings following mine site reclamation. Ecological Engineering 117, 38-49. https://doi.org/10.1016/j.ecoleng.2018.04.001.

Archambo, M. & Kawatra, S. K. (2020). Red mud: Fundamentals and new avenues for utilization. Mineral Processing and Extractive Metallurgy Review 42(7), 427–450. https://doi.org/10.1080/08827508.2020.1781109

Asif, A. H., Li, C., Lim, H. & Sun, H. (2024). Australia's spodumene: Advances in lithium extraction technologies, decarbonization, and circular economy. Industrial & Engineering Chemistry Research 63(5), 2073–2086. https://doi.org/10.1021/acs.iecr.3c04048

Assuncao, J. & Malcata, F. X. (2020). Enclosed "non-conventional" photobioreactors for microalga production: A review. Algal Research 52, 102107. https://doi.org/10.1016/j.algal.2020.102107

Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) (2000). Australian and New Zealand guidelines for fresh and marine water quality. Volume 1. Paper No. 4. Chapters 1-7. October 2000. National Water Quality Management Strategy. Australian and New Zealand Environment and Conservation Council (ANZECC), Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ).

Australian Government (1993). Native Title Act 1993. https://www.legislation.gov.au/C2004A04665/latest/versions

Australian Government (1994). Agricultural and Veterinary Chemicals Code Act 1994. https://classic.austlii.edu.au/cgi-bin/download.cgi/au/legis/cth/consol_act/aavcca1994382

Australian Government (2011). Carbon Credits (Carbon Farming Initiative) Act 2011. https://www.legislation.gov.au/C2011A00101/2020-09-06/text

Australian Government (2016). Working with Indigenous communities: leading practice sustainable development program for the mining industry, Australian Government, Canberra. https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-working-with-indigenous-communities-handbook-english.pdf

Australian Government Clean Energy Regulator (2024a). Quarterly Carbon Market Report March Quarter 2024. Australian Government Clean Energy Regulator. June 19, 2024. https://cer.gov.au/markets/reports-and-data/quarterly-carbon-market-reports/quarterly-carbon-market-report-march-quarter-2024

Australian Government Clean Energy Regulator (2024b). Safeguard Mechanism credit units. https://cer.gov.au/schemes/safeguard-mechanism/safeguard-mechanism-credit-units

Australian Government Clean Energy Regulator (2021). Industrial and Commercial Emissions Reduction Method 2021 - Simple Method Guide (V1). https://cer.gov.au/document/industrial-and-commercial-emissions-reduction-simple-method-guide

Australian Government Department of Agriculture, Water and the Environment (DAWE) (2020). National Pollutant Inventory, DAWE, Canberra, http://www.npi.gov.au.

Australian Government Department of Climate Change, Energy, the Environment and Water (2016). Carbon Credits (Carbon Farming Initiative—Facilities and Minor Corrections) Methodology Determination Variation 2016. https://www.legislation.gov.au/F2016L00363/latest/text

Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW) (2024). Safeguard Mechanism Factsheet. https://www.dcceew.gov.au/sites/default/files/documents/safeguard-mechanism-reforms-factsheet-2023.pdf

Ayre, J. M., Mickan, B. S., Jenkins, S. N. & Moheimani, N. R. (2021). Batch cultivation of microalgae in anaerobic digestate exhibits functional changes in bacterial communities impacting nitrogen removal and wastewater treatment. Algal Research 57, 102338. https://doi.org/10.1016/j.algal.2021.102338

Ayre, J. & Moheimani, N. (2024). Potential of Algal Culture to Treat Anaerobic Digestate of Piggery Waste for Bioremediation and Biomass Production, In: Ravishankar, G. A., Rao, A. R., Kim, S.-K. (Eds.) Algae Mediated Bioremediation. Wiley-VCH GmbH; Weinheim, Germany. Pp. 205–243. https://doi.org/10.1002/9783527843367.ch11

Ayre, J. M., Moheimani, N. R. & Borowitzka, M. A. (2017). Growth of microalgae on undiluted anaerobic digestate of piggery effluent with high ammonium concentrations. Algal Research 24, 218–226. https://doi.org/10.1016/j.algal.2017.03.023

Balzano, S., Sardo, A., Blasio, M., Chahine, T. B., Dell'Anno, F., Sansone, C. & Brunet, C. (2020). Microalgal metallothioneins and phytochelatins and their potential use in bioremediation. Frontiers in Microbiology 11, 517. https://doi.org/10.3389/fmicb.2020.00517.

Banerjee, S. & Ramaswamy, S. (2022). Process model and techno-economic analysis of natural astaxanthin production from microalgae incorporating geospatial variabilities. Bioresource Technology Reports 20, 101260. https://doi.org/10.1016/j.biteb.2022.101260

Banerjee, A., Sarkar, S., Govil, T., Gonzalez-Faune, P., Cabrera-Barjas, G., Bandopadhyay, R., Salem, D. R. & Sani, R. K. (2021). Extremophilic exopolysaccharides: Biotechnologies and wastewater remediation. Frontiers in Microbiology 12, 721365. https://doi.org/10.3389/fmicb.2021.721365

Banfield, B., Moisi, A., Carranceja, J. F., Cohen, J. & Srinivasan, V. (2023). Enabling mine closure and transitions: Opportunities for Australian industry. Prepared for CRC TiME. CSIRO, Australia. https://crctime.com.au/macwp/wp-content/uploads/2023/12/23-00511_FUT_REPORT_MineClosureRoadmap_WEB_231129-1.pdf

Banks, D., Younger, P. L., Amesen, R.-T., Iversen, E. R. & Banks, S. B. (1997). Mine-water chemistry: the good, the bad and the ugly. Environmental Geology 32, 157-174. doi.org/10.1007/s002540050204

Bansod, S.R. & Nandkar, P.B. (2016). Biosorption of Mn (II) by *Spirogyra verrucosa* collected from manganese mine water. Plant Science Today 3, 282. https://doi.org/10.14719/pst.2016.3.3.244

Beck, K. K., Mariani. M., Fletcher, M.-S., Schneider, L., Aquino-López, M. A., Gadd, P. S., Heijnis, H., Saunders, K. M. & Zawadzki, A. (2020). The impacts of intensive mining on terrestrial and aquatic ecosystems: A case of sediment pollution and calcium decline in cool temperate Tasmania, Australia. Environmental Pollution 265(Part A), 114695. doi.org/10.1016/j.envpol.2020.114695.

Benedetti, M., Vecchi, V., Barera, S. & Dall'Osto, L. (2018). Biomass from microalgae: the potential of domestication towards sustainable biofactories. Microbial Cell Factories 17, 173. https://doi.org/10.1186/s12934-018-1019-3

BenMoussa-Dahmen, I., Chtourou, H., Rezgui, F., Sayadi, S. & Dhouib, A. (2016). Salinity stress increases lipid, secondary metabolites and enzyme activity in *Amphora subtropica* and *Dunaliella* sp. for biodiesel production. Bioresource Technology 218, 816–825. https://doi.org/10.1016/j.biortech.2016.07.022

Bennett, A. C., Murugapiran, S. K., Kees, E. D., Sauer, H. M. & Hamilton, T. L. (2022). Temperature and geographic location impact the distribution and diversity of photoautotrophic gene variants in alkaline Yellowstone hot springs. Microbiology Spectrum 10(3), e01465–21. https://doi.org/10.1128/spectrum.01465-21

Berry, J. P., Gantar, M., Perez, M. H., Berry, G. & Noriega, F. G. (2008). Cyanobacterial toxins as allelochemicals with potential applications as algaecides, herbicides and insecticides. Marine Drugs 6(2), 117–46. https://doi.org/10.3390/md6020117

Berry, F., Retamal, M., Kuzhiumparambil, U. & Ralph, P. (2022). Market and sustainability potential for algal bioplastics in Australia. UTS Institute for Sustainable Futures and UTS Climate Change Cluster. https://www.uts.edu.au/sites/default/files/2023-01/sci-ISF-C3-Bioplastics-Final-Report-2022.pdf

Bhaskar, P. & Bhosle, N. B. (2005). Microbial extracellular polymeric substances in marine biogeochemical processes. Current Science 88(1), 45–53.

Borowitzka, M. A. (2016). Systematics, Taxonomy and Species Names: Do They Matter? In: Borowitzka M. A., Beardall, J. & Ravenhill, J. (Eds.) The Physiology of Microalgae. Springer International Publishing, Cham. Pp. 655–681. https://doi.org/10.1007/978-3-319-24945-2_24

Borowitzka, M. A. & Vonshak, A. (2017). Scaling up microalgal cultures to commercial scale. European Journal of Phycology 52(4), 407–418. https://doi.org/10.1080/09670262.2017.1365177

Boshoff, G., Duncan, J. & Rose, P. D. (2004). The use of micro-algal biomass as a carbon source for biological sulphate reducing systems. Water Research 38, 2659–2666. https://doi.org/10.1016/j.watres.2004.03.031

Brake, S. S., Hasiotis, S. T. & Dannely, H. K. (2004). Diatoms in acid mine drainage and their role in the formation of iron-rich stromatolites. Geomicrobiology Journal 21, 331-340. https://doi.org/10.1080/01490450490454074

Branco-Vieira, M., Mata, T. M., Martins, A. A., Freitas, M. A. V. & Caetano, N. S. (2020). Economic analysis of microalgae biodiesel production in a small-scale facility. Energy Reports 6, 325–332. https://doi.org/10.1016/j.egyr.2020.11.156

Brar, K. K., Etteieb, S., Magdouli, S., Calugaru, L. & Brar, S. K. (2022). Approach for the management of acid mine drainage (AMD) for the recovery of heavy metals along with lipid production by *Chlorella vulgaris*. Journal of Environmental Management 308, 114507. https://doi.org/10.1016/j.jenvman.2022.114507

Britt, A., Summerfield, D., Senior, A., Kay, P., Huston, D., Hitchman, A., Hughes, A., Champion, D., Simpson, R., Sexton, M. & Schofield, A. (2017). Geoscience Australia 2017. Australia's Identified Mineral Resources 2017. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/1327-1466

Buhani, Wijayanti, T. A., Suharso, Sumadi & Ansori, M. (2021). Application of modified green algae *Nannochloropsis* sp. as adsorbent in the simultaneous adsorption of methylene blue and Cu(II) cations in solution. Sustainable Environment Research 31 (1), 1-12. https://doi.org/10.1186/s42834-021-00090-y

Bwapwa, J. K., Jaiyeola, A. T. & Chetty, R. (2017). Bioremediation of acid mine drainage using algae strains: A review. South African Journal of Chemical Engineering 24, 62-70. https://doi.org/10.1016/j.sajce.2017.06.005

Callejón, M. J. J., Medina, A. R., Sánchez, M. D. M., Moreno, P. A. G., López, E. N., Cerdán, L. E. & Grima, E. M. (2022). Supercritical fluid extraction and pressurized liquid extraction processes applied to eicosapentaenoic acid-rich polar lipid recovery from the microalga *Nannochloropsis* sp. Algal Research 61, 102586. https://doi.org/10.1016/j.algal.2021.102586

Campbell, A., Alexandra, J. & Curtis, D. (2017). Reflections on four decades of land restoration in Australia. Rangeland Journal 39(6), 405–416. doi.org/10.1071/RJ17056.

Campos, V., Morais, L. C. & Mafavisse, I. M. (2022). Synthesis of a plant-based dust suppressant and testing on coal from Moatize, Mozambique. Chemical and Biochemical Engineering Quarterly 36(3), 207-215. https://doi.org/10.15255/CABEQ.2022.2058

Canon-Rubio, K. A., Sharp, C. E., Bergerson, J., Strous, M. & De la Hoz Siegler, H. (2015). Use of highly alkaline conditions to improve cost-effectiveness of algal biotechnology. Applied Microbiology and Biotechnology 100(4), 1611–1622. https://doi.org/10.1007/s00253-015-7208-7

Cassin, P. E. (1974). Isolation, growth, and physiology of acidophilic chlamydomonads 1, 2. Journal of Phycology 10(4), 439–447. https://doi.org/10.1111/j.1529-8817.1974.tb02737.x

Cassuriaga, A. P. A., Freitas, B. C. B., Morais, M. G. & Costa, J. A. V. (2018). Innovative polyhydroxybutyrate production by *Chlorella fusca* grown with pentoses. Bioresource Technology 265, 456-463. https://doi.org/10.1016/j.biortech.2018.06.026

Chakraborty, N., Banerjee, A., Lahiri, S., Panda, A., Ghosh, A. N. & Pal, R. (2008). Biorecovery of gold using cyanobacteria and an eukaryotic alga with special reference to nanogold formation – a novel phenomenon. Journal of Applied Phycology 21(1), 145–152. https://doi.org/10.1007/s10811-008-9343-3

Chalkley, R., Child, F., Al-Thaqafi, K., Dean, A. P., White, K. N. & Pittmann, J. K. (2019) Macroalgae as spatial and temporal bioindicators of coastal metal pollution following remediation and diversion of acid mine drainage. Ecotoxicology and Environmental Safety 182, 109458. https://doi.org/10.1016/j.ecoenv.2019.109458

Chan, A., Salsali, H. & McBean, E. (2013). Heavy metal removal (copper and zinc) in secondary effluent from wastewater treatment plants by microalgae. ACS Sustainable Chemistry & Engineering 2(2), 130–137. https://doi.org/10.1021/sc400289z

Chandra, R. & Kang, H. (2015). Mixed heavy metal stress on photosynthesis, transpiration rate, and chlorophyll content in poplar hybrids. Forest Science and Technology 12(2), 55–61. https://doi.org/10.1080/21580103.2015.1044024

Chatsungnoen, T. & Chisti, Y. (2016). Oil production by six microalgae: impact of flocculants and drying on oil recovery from the biomass. Journal of Applied Phycology 28(5), 2697–2705. https://doi.org/10.1007/s10811-016-0823-6

Chen, W. H., Lin, B. J., Huang, M. Y. & Chang, J. S. (2015). Thermochemical conversion of microalgal biomass into biofuels: A review. Bioresource Technology 184, 314-327. https://doi.org/10.1016/j.biortech.2014.11.050

Cheng, K. Y., Kaksonen, A. H. & Douglas, G. B. (2014). Sequential *in situ* hydrotalcite precipitation and biological denitrification for the treatment of high-nitrate industrial effluent. Bioresource Technology 172, 373-381. https://doi.org/10.1016/j.biortech.2014.09.050

Cheng, J., Li, K., Yang, Z., Lu, H., Zhou, J. & Cen, K. (2016). Gradient domestication of *Haematococcus pluvialis* mutant with 15% CO_2 to promote biomass growth and astaxanthin yield. Bioresource Technology 216, 340–344. https://doi.org/10.1016/j.biortech.2016.05.095

Cheng, K. Y., Mohottige, T. W., Ginige, M. P. & Kaksonen, A. H. (2023). New perspectives for bio-technical treatment of oxalate-containing waste streams from bauxite processing. Hydrometallurgy 220, 106105. doi.org/10.1016/j.hydromet.2023.106105.

Chia, S. R., Chew, K. W., Leong, H. Y., Ho, S. H., Munawaroh, H. S. H. & Show, P. L. (2021). CO_2 mitigation and phycoremediation of industrial flue gas and wastewater via microalgae-bacteria consortium: possibilities and challenges. Chemical Engineering Journal 425, 131436. https://doi.org/10.1016/j.cej.2021.131436

Chiaverini, N. & De Ley, M. (2010). Protective effect of metallothionein on oxidative stress-induced DNA damage. Free Radical Research 44(6), 605– 613. https://doi.org/10.3109/10715761003692511

Christensen, B., Laake, M. & Lien, T. (1996). Treatment of acid mine water by sulfate-reducing bacteria: Results from a bench scale experiment. Water Research 30, 1617–1624. https://doi.org/10.1016/0043-1354(96)00049-8

Chisti, Y. (2007). Biodiesel from microalgae. Biotechnology Advances 25(3), 294-306. https://doi.org/10.1016/j.biotechadv.2007.02.001

Chisti, Y. (2008). Biodiesel from microalgae beats bioethanol. Trends in Biotechnology 26(3), 126-131. https://doi.org/10.1016/j.tibtech.2007.12.002

Choudhury, N. R. (2021). Pet Food Microalgae Market. Future Market Insights. July 8, 2021. https://www.futuremarketinsights.com/reports/microalgae-pet-food-sector.

Choudhury, N. R. (2024). Microalgae-Based Aquafeed Market. Future Market Insights. May 10, 2024. https://www.futuremarketinsights.com/reports/microalgae-based-aquafeed-market.

Chu, S. P. (1942). The influence of the mineral composition of the medium on the growth of planktonic algae: Part I. Methods and culture media. The Journal of Ecology 30(2), 284–325. http://links.jstor.org/sici?sici=0022-0477%28194208%2930%3A2%3C284%3ATIOTMC%3E2.0.CO%3B2-4

Chunzhuk, E. A., Grigorenko, A. V., Kiseleva, S. V., Chernova, N. I., Ryndin, K. G., Kumar, V. & Vlaskin, M. S. (2023). The influence of elevated CO_2 concentrations on the growth of various microalgae strains. Plants 12(13), 2470. https://doi.org/10.3390/plants12132470

Ciapponi, R., Turri, S. & Levi, M. (2019). Mechanical reinforcement by microalgal biofiller in novel thermoplastic biocompounds from plasticized gluten. Materials 12(9), 1476. https://doi.org/10.3390/ma12091476

Cizkova, M., Mezricky, D., Rucki, M., Toth, T. M., Nahlik, V., Lanta, V., Bisova, K., Zachleder, V. & Vitova, M. (2019). Bio-mining of lanthanides from red mud by green microalgae. Molecules 24(7). https://doi.org/10.3390/molecules24071356

Cleveland, C. C. & Townsend, A. R. (2006). Nutrient additions to a tropical rain forest drive substantial soil carbon dioxide losses to the atmosphere. Proceedings of the National Academy of Sciences 103(27), 10316– 10321. https://doi.org/10.1073/pnas.060098910

Cole, A. J., Neveux, N., Whelan, A., Morton, J., Vis, M., de Nys, R. & Paul, N. A. (2016). Adding value to the treatment of municipal wastewater through the intensive production of freshwater macroalgae. Algal Research 20, 100–109. https://doi.org/10.1016/j.algal.2016.09.026

Cole, J. J. & Prairie, Y. T. (2014). Dissolved CO_2 in Freshwater Systems. In: Reference Module in Earth Systems and Environmental Sciences, Elsevier Inc: Amsterdam, The Netherlands. Pp. 30-34. https://doi.org/10.1016/B978-0-12-409548-9.09399-4

Colosi, L. M., Zhang, Y., Clarens, A. F., & White, M. A. (2012). Will algae produce the green? Using published life cycle assessments as a starting point for economic evaluation of future algae-to-energy systems. Biofuels 3(2), 129–142. https://doi.org/10.4155/bfs.12.4

Copertino, M. d. S., Tormena, T. & Seeliger, U. (2008). Biofiltering efficiency, uptake and assimilation rates of *Ulva clathrata* (Roth) J. Agardh (Clorophyceae) cultivated in shrimp aquaculture waste water. Journal of Applied Phycology 21(1), 31–45. https://doi.org/10.1007/s10811-008-9357-x

Corales-Ultra, O. G., Peja Jr, R. P. & Casas Jr., E. V. (2019). Baseline study on the levels of heavy metals in seawater and macroalgae near an abandoned mine in Manicani, Guiuan, Eastern Samar, Philippines. Marine Pollution Bulletin 149, 110549. https://doi.org/10.1016/j.marpolbul.2019.110549

Costas, E., Flores-Moya, A., Perdigones, N., Maneiro, E., Blanco, J. L., García, M. E. & López-Rodas, V. (2007). How eukaryotic algae can adapt to the Spain's Rio Tinto: a neo-Darwinian proposal for rapid adaptation to an extremely hostile ecosystem. New Phytologist 175(2), 334–339. https://doi.org/10.1111/j.1469-8137.2007.02095.x

Costa, S. S., Miranda, A. L., Andrade, B. B., Assis, D. d. J., Souza, C. O., de Morais, M. G., Costa, J. A. V., Druzian, J. I. (2018). Influence of nitrogen on growth, biomass composition, production, and properties of polyhydroxyalkanoates (PHAs) by microalgae. International Journal of Biological Macromolecules 116, 552-562. https://doi.org/10.1016/j.ijbiomac.2018.05.064

Craggs, R., Sutherland, D. & Campbell, H. (2012). Hectare-scale demonstration of high rate algal ponds for enhanced wastewater treatment and biofuel production. Journal of Applied Phycology 24(3), 329–337. https://doi.org/10.1007/s10811-012-9810-8

Craw, D., Rufaut, C. & Pillai, D. (2023). Evolution of alkaline mine drainage and unique biodiversity on soil-free mine substrates, southern New Zealand. Mine Water and the Environment 42(1), 3–23. https://doi.org/10.1007/s10230-023-00913-x

Cresswell, I. D., Janke, T. & Johnston, E. L. (2021). Australia state of the environment 2021: overview, independent report to the Australian Government Minister for the Environment, Commonwealth of Australia, Canberra. https://doi.org/10.26194/f1rh-7r05

CSIRO (2024). Feeding seaweed to cows: Our livestock methane research lights up. https://www.csiro.au/en/news/All/Articles/2019/April/feeding-seaweed-to-cows-our-livestock-methane-research-lights-up

Cuello, J. L., Hoshino, T., Kuwahara, S. & Brown, C. L. (2016) Chapter 19 - Scale-Up—Bioreactor Design and Culture Optimization. In: Eckert, C. A., Trinh, C. T. (eds) Biotechnology for Biofuel Production and Optimization, Elsevier. Pp. 497-511, https://doi.org/10.1016/B978-0-444-63475-7.00019-4.

Dang, B. T., Bui, X. T., Tran, D. P. H., Ngo, H. H., Nghiem, L. D., Hoang, T. K. D., Nguyen, P. T., Nguyen, H. H., Vo, T. K. Q., Lin, C., Lin, K. Y. A. & Varjani, S. (2022) Current application of algae derivatives for bioplastic production: a review. Bioresource Technology 347, 126698. https://doi.org/10.1016/j.biortech.2022.126698Get rights and content

Daraz, U., Li, Y., Ahmad, I., Iqbal, R. & Ditta, A. (2023). Remediation technologies for acid mine drainage: Recent trends and future perspectives. Chemosphere 311(Pt 2), 137089. https://doi.org/10.1016/j.chemosphere.2022.137089

Das, B. K., Roy, A., Koschorreck, M., Mandal, S. M., Wendt-Potthoff, K. & Bhattacharya, J. (2009). Occurrence and role of algae and fungi in acid mine drainage environment with special reference to metals and sulfate immobilization. Water Research 43(4), 883-894. https://doi.org/10.1016/j.watres.2008.11.046

da Silva, G. O. A., Dunlop, J., Nicolson, L. & Purtill, J. (2024). Review of techniques to address topsoil deficit in open cut coal mines under rehabilitation in Queensland: Student report. Queensland Mine Rehabilitation Commissioner, Queensland Government, Brisbane.

da Silva, G. O. A., Southam, G. & Gagen, E. J. (2023). Accelerating soil aggregate formation: a review on microbial processes as the critical step in a post-mining rehabilitation context. Soil Research 61(3), 209-223. https://doi.org/10.1071/SR22092

Dean, A. P., Hartley, A., McIntosh, O. A., Smith, A., Feord, H. K., Holmberg, N. H., King, T., Yardley, E., White, K. N. & Pittman, J. K. (2019). Metabolic adaptation of a C*hlamydomonas acidophila* strain isolated from acid mine drainage ponds with low eukaryotic diversity. Science of the Total Environment 647, 75–87. https://doi.org/10.1016/j.scitotenv.2018.07.445

Deepika, C., Wolf, J., Roles, J., Ross, I. & Hankamer, B. (2022). Sustainable Production of Pigments from Cyanobacteria. In: Bühler, K., Lindberg, P. (eds) Cyanobacteria in Biotechnology. Advances in Biochemical Engineering/Biotechnology, 183. Springer, Cham. https://doi.org/10.1007/10_2022_211.

Department of Environment and Science (2017). Model operating conditions ERA 60 – waste disposal. https://www.des.qld.gov.au/policies?a=272936:policy_registry/pr-co-landfill.pdf#:~:text=The%20Environmental%20Protection%20Act%201994%20%28EP%20Act%29%20provides,to%20landfill%20operations%20across%20the%20State%20of%20Queensland.

Department of Environment, Science and Innovation (2024a). Department of Environment, Science and Innovation, Guideline: Mining Model mining conditions (ESR/2016/1936; Version 6.03, 19 FEB 2024). https://www.des.qld.gov.au/policies?a=272936:policy_registry/rs-gl-model-mining-conditions.pdf

Department of Environment, Science and Innovation (2024b). End of Waste Code - Water Treatment Residuals (ENEW07503318). https://www.desi.qld.gov.au/policies?a=272936:policy_registry/wr-eowc-approved-water-treatment-residuals.pdf

Department of Environment, Science and Innovation (2024c). End of Waste Code - Irrigation of Associated Water (including coal seam gas water) (ENEW07546918). https://www.desi.qld.gov.au/policies?a=272936:policy_registry/wr-eowc-irrigation-associated-water.pdf

Department of Environment, Science and Innovation (2024d). Statutory guideline Progressive rehabilitation and closure plan (PRC plans). https://www.des.qld.gov.au/policies?a=272936:policy_registry/rs-gl-prc-plan.pdf.

Deprá, M. C., Dias, R. R., Severo, I. A., de Menezes, C. R., Zepka, L. Q. & Jacob-Lopes, E. (2020). Carbon dioxide capture and use in photobioreactors: The role of the carbon dioxide loads in the carbon footprint. Bioresource Technology 314, 123745. https://doi.org/10.1016/j.biortech.2020.123745

Dhar, D. W., Prasanna, R., Pabbi, S. & Vishwakarma, R. (2015). Significance of Cyanobacteria as Inoculants in Agriculture, In: Das, D. (eds) Algal Biorefinery: An Integrated Approach. Springer International Publishing, Cham. Pp. 339–374. https://doi.org/10.1007/978-3-319-22813-6_16

Díaz-Alejo, H. M., López-Rodas, V., García-Balboa, C., Tarín, F., Barrado, A. I., Conde, E. & Costas, E. (2021). The upcoming ^{6}Li isotope requirements might be supplied by a microalgal enrichment process. Microorganisms 9(8), 1753. https://doi.org/10.3390/microorganisms9081753

Difusa, A., Mohanty, K. & Goud, V. V. (2015). Advancement and Challenges in Harvesting Techniques for Recovery of Microalgae Biomass. In: Environmental Sustainability: Role of Green Technologies. New Delhi, India: Springer. pp. 152-167. https://doi.org/10.1007/978-81-322-2056-5_9

Ding, H., Zhang, Q., Xu, H., Yu, X., Chen, L., Wang, Z. & Feng, J. (2021). Selection of copper and zinc dosages in pig diets based on the mutual benefit of animal growth and environmental protection. Ecotoxicology and Environmental Safety 216, 112177. https://doi.org/10.1016/j.ecoenv.2021.112177

Dixon, R. K., Solomon, A., Brown, S., Houghton, R., Trexier, M. & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. Science 263(5144), 185–190. https://www.science.org/doi/10.1126/science.263.5144.185

Dong, H., Yu, H., Xu, R., Cheng, W., Ye, Y., Xie, S., Zhao, J. & Cheng, Y. (2023). Review and prospects of mining chemical dust suppressant: classification and mechanisms. Environmental Science and Pollution Research 30(1), 18-35. https://doi.org/10.1007/s11356-022-23840-w

Downie, A. E., Van Zwieten, L., Smernik, R. J., Morris, S. & Munroe, P. R. (2011). *Terra Preta Australis*: Reassessing the carbon storage capacity of temperate soils. Agriculture, Ecosystems & Environment 140(12), 137–147. https://doi.org/10.1016/j.agee.2010.11.020

Du, T. H., Bogush, A., Masek, O., Purton, S. & Campos, L. C. (2022). Algae, biochar and bacteria for acid mine drainage (AMD) remediation: A review. Chemosphere 204, 135284. https://doi.org/10.1016/j.chemosphere.2022.135284

Duarte, J. H., de Morais, E. G., Radmann, E. M. & Costa, J. A. V. (2017). Biological CO_2 mitigation from coal power plant by *Chlorella fusca* and *Spirulina* sp. Bioresource Technology 234, 472-475. https://doi.org/10.1016/j.biortech.2017.03.066

Dubey, K. & Dubey, K. P. (2011). A study of the effect of red mud amendments on the growth of cyanobacterial species. Bioremediation Journal 15(3), 133–139. https://doi.org/10.1080/10889868.2011.598483

Edraki, M., Golding, S. D., Baublys, K. A. & Lawrence, M. G. (2005). Hydrochemistry, mineralogy and sulfur isotope geochemistry of acid mine drainage at the Mt. Morgan mine environment, Queensland, Australia. Applied Geochemistry 20(4), 789–805. https://doi.org/10.1016/j.apgeochem.2004.11.004.

Eibl, J. K., Corcoran, J. D., Senhorinho, G. N. A., Zhang, K. J., Hosseini, N. S., Marsden, J., Laamanen, C. A., Scott, J. A. & Ross, G. M. (2014). Bioprospecting for acidophilic lipid-rich green microalgae isolated from abandoned mine site water bodies. AMB Express 4, 7. https://doi.org/10.1186/2191-0855-4-7

Elbaz-Poulichet, F., Dupuy, C., Cruzado, A., Velasqaez, Z., Achterberg, E. P. & Braungardt, C. B. (2000). Influence of sorption process by iron oxides and algae fixation on arsenic and phosphate cycle in an acidic estuary (Tinto River, Spain). Water Research 34, 3222-3230. https://doi.org/10.1016/S0043-1354(00)00073-7

Ellison, M. B., de Nys, R., Paul, N. A. & Roberts, D. A. (2014). Growth and metal bioconcentration by conspecific freshwater macroalgae cultured in industrial waste water. PeerJ 2, e401. https://doi.org/10.7717/peerj.401

Endo, H. & Gao, X. (2022). A new classification tool and a systematic review of macroalgal studies disentangle the complex interactive effects of warming and nutrient enrichment on primary production. Frontiers in Marine Science 9, 774801, 1-9. https://doi.org/10.3389/fmars.2022.774801

Erskine, P. D. & Fletcher, A. T. (2013). Novel ecosystems created by coal mines in central Queensland's Bowen Basin. Ecological Processes 2, 1-12. https://doi.org/10.1186/2192-1709-2-33

Erulan, V., Soundarapandian, P., Thirumaran, G. & Ananthan, G. (2009). Studies on the effect of *Sargassum polycystum* (C. Agardh, 1824) extract on the growth and biochemical composition of *Cajanus cajan* (L.) mill sp. American-Eurasian Journal of Agricultural and Environmental Science 6(4), 392–399.

Everingham, J.-A., Rolfe, J., Lechner, A. M., Kinnear, S. & Akbar, D. (2018). A proposal for engaging a stakeholder panel in planning post-mining land uses in Australia's coal-rich tropical savannahs. Land Use Policy 79, 397–406. https://doi.org/10.1016/j.landusepol.2018.08.038

Fact.MR (2023a). Biochar Market. https://www.factmr.com/report/3781/biochar-market

Fact.MR (2023b). Dust Suppressants Market. https://www.factmr.com/report/dust-suppressants-market

Fatini, M., Basri, E. & Maznah, W. W. (2021). Effect of different nitrogen sources on cell growth and biochemical compositions of *Chlorococcum* sp. cultivated under laboratory conditions. IOP Conf. Series: Earth and Environmental Science 711, 012010. https://doi.org/10.1088/1755-1315/711/1/012010

Fernández, L. A. G., Ramos, V. C., Polo, M. S. & Castillo, N. A. M. (2023). Fundamentals in applications of algae biomass: A review. Journal of Environmental Management 338, 11. https://doi.org/10.1016/j.jenvman.2023.117830

Ferreira, A., Melkonyan, L., Carapinha, S., Ribeiro, B., Figueiredo, D., Avetisova, G. & Gouveia, L. (2021). Biostimulant and biopesticide potential of microalgae growing in piggery wastewater. Environmental Advances 4, 100062. https://doi.org/10.1016/j.envadv.2021.100062

Finkel, Z. V., Follows, M. J., Liefer, J. D., Brown, C. M., Benner, I. & Irwin, A. J. (2016). Phylogenetic diversity in the macromolecular composition of microalgae. PLoS One 11(5), e0155977. https://doi.org/10.1371/journal.pone.0155977

Firpo, B. A., Weiler, J. & Schneider, I. A. (2021). Technosol made from coal waste as a strategy to plant growth and environmental control. Energy Geoscience 2(2), 160-166. https://doi.org/10.1016/j.engeos.2020.09.006

Fitzgerald, B. (2014) Marron farm generates work for Aboriginal community. https://www.abc.net.au/news/rural/2014-07-10/marron-farm-ngalang-boodja-collie/5583810

Flor, J. M., Schenberg, A. C. G., Nascimento, H. d. A. F. d. & Oliveira, M. J. D. (2022). Analysis of the microalgae community found in acid lake of uranium mine: bioprospecting for evaluation of biotechnological potential. Preprint (not peer-reviewed) available at Research Square. https://doi.org/10.21203/rs.3.rs-2223509/v1

Food Standards Australia New Zealand (2023). Food Standards Code. https://www.foodstandards.gov.au/food-standards-code

Fuentes, J. L., Huss, V. A. R., Montero, Z., Torronteras, R., Cuaresma, M., Garbayo, I. & Vilchez, C. (2016). Phylogenetic characterization and morphological and physiological aspects of a novel acidotolerant and halotolerant microalga *Coccomyxa onubensis* sp. nov. (Chlorophyta, Trebouxiophyceae). Journal of Applied Phycology 28(6), 3269–3279. https://doi.org/10.1007/s10811-016-0887-3

Fyson, A., Nixdorf, B. & Kalin, M. (2006). The acidic lignite pit lakes of Germany—Microcosm experiments on acidity removal through controlled eutrophication. Ecological Engineering 28(3), 288–295. https://doi.org/10.1016/j.ecoleng.2006.06.012

Gaete Olivares, H., Moyano Lagos, N., Jara Gutierrez, C., Carrasco Kittelsen, R., Lobos Valenzuela, G. & Hidalgo Lillo, M. E. (2016). Assessment oxidative stress biomarkers and metal bioaccumulation in macroalgae from coastal areas with mining activities in Chile. Environmental Monitoring and Assessment 188(1), 25. https://doi.org/10.1007/s10661-015-5021-5

Garcia, N. S., Sexton, J., Riggins, T., Brown, J., Lomas, M. W. & Martiny, A. C. (2018). High variability in cellular stoichiometry of carbon, nitrogen, and phosphorus within classes of marine eukaryotic phytoplankton under sufficient nutrient conditions. Frontiers in Microbiology 9, 543. https://doi.org/10.3389/fmicb.2018.00543

Gautam, S. & Kapoor, D. (2022). Application of halophilic algae for water desalination. In: Mostafa El-Sheekh, M. & Abomohra, A. E.-F. (Eds.) Handbook of Algal Biofuels, Aspects of Cultivation, Conversion, and Biorefinery. Elsevier, pp. 167-179. https://doi.org/10.1016/B978-0-12-823764-9.00002-9

Gauthier, M. R., Senhorinho, G. N. A, Basiliko, N., Desjardins, S. & Scott, J. A. (2022). Green photosynthetic microalgae from low pH environments associated with mining as a potential source of antioxidants. Industrial Biotechnology 18(3), 168-175. https://doi.org/10.1089/ind.2022.00

Glaser, B. & Birk, J. J. (2012). State of the scientific knowledge on properties and genesis of anthropogenic dark earths in central Amazonia (*terra preta de Indio*´). Geochimica et Cosmochimica Acta 82, 39–51. https://doi.org/10.1016/j.gca.2010.11.029

Goliya, K. (2023). Commodities 2024: Australian carbon prices see upside as compliance demand grows. S&P Global Commodity Insights. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/121523-australian-carbon-prices-see-upside-in-2024-as-compliance-demand-grows

Gomes, P., Valente, T., Albuquerque, T., Henriques, R., Flor-Arnau, N., Pamplona, J. & Macías, F. (2021). Algae in acid mine drainage and relationships with pollutants in a degraded mining ecosystem. Minerals 11(2), 110. https://doi.org/10.3390/min11020110

Gonzalez-Toril, E., Santofimia, E., Lopez-Pamo, E., Garcia-Moyano, A., Aguilera, A. & Amils, R. (2014). Comparative microbial ecology of the water column of an extreme acidic pit lake, Nuestra Señora del Carmen, and the Rio Tinto basin (Iberian pyrite belt). International Microbiology 17(4), 225–233. https://doi.org/10.2436/20.1501.01.225

Government of Western Australia (1986) Environmental Protection Act 1986. https://www.legislation.wa.gov.au/legislation/prod/filestore.nsf/FileURL/mrdoc_47972.pdf/$FILE/Environmental%20Protection%20Act%201986%20-%20%5B09-w0-00%5D.pdf?OpenElement

Gräfe, M., Landers, M., Tappero, R., Klauber, C., Hutomo, G., Gan Bee, G. B., Grabsch, A., Austin, P. & Davies, I. (2010). Chemistry of trace and heavy metals in bauxite residues (red mud) from Western Australia. 19th World Congress of Soil Science, Soil Solutions for a Changing World. 1-6 August 2010, Brisbane, Australia. Pp. 39-42.

Gräfe, M., Power, G. & Klauber, C. (2011). Bauxite residue issues: Iii. alkalinity and associated chemistry. Hydrometallurgy 108(1-2), 60–79. https://doi.org/10.1016/j.hydromet.2011.02.004

Grand View Research (2024a). Algae Biofuel Market Size, Share & Trends Analysis Report by Application (Transportation, Others), by Region (North America, Europe, Asia Pacific, Central & South America, Middle East & Africa), and Segment Forecasts, 2023 - 2030. https://www.grandviewresearch.com/industry-analysis/algae-biofuel-market

Grand View Research (2024b). Astaxanthin Market Size, Share & Trends Analysis Report by Product (Oil, Softgel, Liquid), by Source (Natural, Synthetic), by Application (Aquaculture & Animal Feed, Nutraceuticals), by Region, and Segment Forecasts, 2024 - 2030. https://www.grandviewresearch.com/industry-analysis/global-astaxanthin-market

Grand View Research (2024c). Omega 3 Market Size, Share & Trends Analysis Report by Type (EPA, DHA, ALA), by Source (Marine, Plant), by Application (Supplements & Functional Foods), by Region, and Segment Forecasts, 2024 - 2030. https://www.grandviewresearch.com/industry-analysis/omega-3-market

Gray, N. F. (1997). Environmental impact and remediation of acid mine drainage: A management problem. Environmental Geology 30, 62-71. https://doi.org/10.1007/s002540050133

Gross, W. & Schnarrenberger, C. (1995). Heterotrophic growth of two strains of the acido-thermophilic red alga *Galdieria sulphuraria*. Plant and cell physiology 36(4), 633–638. https://doi.org/10.1093/oxfordjournals.pcp.a078803

Guccione, A., Biondi, N., Sampietro, G., Rodolfi, L., Bassi, N. & Tredici, M. R., 2014. *Chlorella* for protein and biofuels: from strain selection to outdoor cultivation in a Green Wall Panel photobioreactor. Biotechnology for Biofuels and Bioproducts 7, 84. https://doi.org/10.1186/1754-6834-7-84

Guedes, A. C., Amaro, H. M., Pereira R. D. & Malcata F. X. (2011). Effects of temperature and pH on growth and antioxidant content of the microalga *Scenedesmus obliquus.* Biotechnology Progress 27, 1218-1224. https://doi.org/10.1002/btpr.649

Guiry, M. D. (2024). How many species of algae are there? A reprise. Four kingdoms, 14 phyla, 63 classes and still growing. Journal of Phycology 60(2), 214–228. https://doi.org/10.1111/jpy.13431

Günan Yücel, H., Karatay, S. E., Aksu, Z. & Dönmez, G. (2021). Lithium (i) biofortified *Dunaliella salina* as a potential functional nutrition supplement. Algal Research 56, 102257. https://doi.org/10.1016/j.algal.2021.102257

Günerken, E., D'Hondt, E., Eppink, M. H. M., Garcia-Gonzalez, L., Elst, K. & Wijffels, R. H. (2015). Cell disruption for microalgae biorefineries. Biotechnology Advances 33(2), 243-260, https://doi.org/10.1016/j.biotechadv.2015.01.008

Harvey, B. E. (2016). The eye of the beholder — utility and beauty in mine closure. In Fourie, A. B. & Tibbett, M. (Eds.), Proceedings of the 11th International Conference on Mine Closure, Australian Centre for Geomechanics, 2016, Perth (pp. 17-23).

Hatfield-Dodds, S. & Boulus, P. (2023). Australia's Carbon Market Is Changing Gears. Are You Ready? Ernst & Young Global Limited. September 5, 2023. https://www.ey.com/en_au/insights/sustainability/australia-s-carbon-market-is-changing-gears-are-you-ready

Heads of Environment Protection Authorities (EPAs) Australia and New Zealand (2020) PFAS National Environmental Management Plan Version 2.0. National Chemicals Working Group of the Heads of EPAs Australia and New Zealand. https://www.dcceew.gov.au/sites/default/files/documents/pfas-nemp-2.pdf

Heilmann, S. M., Davis, H. T., Jader, L. R., Lefebvre, P. A., Sadowsky, M. J., Schendel, F. J., von Keitz, M. G. & Valentas, K. J. (2010). Hydrothermal carbonization of microalgae. Biomass and Bioenergy 34 (6), 875–882. https://doi.org/10.1016/j.biombioe.2010.01.032

Herbert, R. B. & Höckert, L. (2009). Mine waste stabilization with biosludge and paper mill waste. Securing the Future and the 8th International Conference on Acid Rock Drainage (ICARD). Swedish Association of Mines, Mineral and Metal Producers, 22-26 June, 2009, Skelleftea, Sweden. Pp. 1-8. https://www.diva-portal.org/smash/get/diva2:298312/FULLTEXT01.pdf

Hirooka, S. & Miyagishima, S.-y. (2016). Cultivation of acidophilic algae *Galdieria sulphuraria* and *Pseudochlorella* sp. YKT1 in media derived from acidic hot springs. Frontiers in Microbiology 07, 2022. https://doi.org/10.3389/fmicb.2016.02022

Hu, T., Chen, A., Jiang, Y., Sun, C., Luo, S. & Shao, J. (2022). Application of a newly recorded diazotrophic cyanobacterium in acidified and Cd contaminated paddy soil: Promotes rice yield and decreases Cd accumulation. Science of The Total Environment 814, 152630. https://doi.org/10.1016/j.scitotenv.2021.152630

Hudson, T. L., Fox, F. D. & Plumlee, G. S. (1999). Metal Mining and the Environment. American Geological Institute. 68 p. https://www.americangeosciences.org/sites/default/files/metalenvfull.pdf

Hwang, S. W., Choi, H. I. & Sim, S. J. (2019). Acidic cultivation of *Haematococcus pluvialis* for improved astaxanthin production in the presence of a lethal fungus. Bioresource Technology 278, 138–144. https://doi.org/10.1016/j.biortech.2019.01.080

Ichihara, K., Miyaji, K. & Shimada, S. (2012). Comparing the low-salinity tolerance of *Ulva* species distributed in different environments. Phycological Research 61, 52-57. https://doi.org/10.1111/j.1440-1835.2012.00668.x

Ighalo, J. O., Kurniawan, S. B., Iwuozor, K. O., Aniagor, C. O., Ajala, O. J., Oba, S. N., Iwuchukwu, F. U., Ahmadi, S. & Igwegbe, C. A. (2022). A review of treatment technologies for the mitigation of the toxic environmental effects of acid mine drainage (AMD). Process Safety and Environmental Protection 157, 37–58. https://doi.org/10.1016/j.psep.2021.11.008

IMARK (2024) Algae Products Market Report by Type (Lipids, Carrageenan, Carotenoids, Algal Protein, Alginate, and Others), Source (Brown Algae, Blue-Green Algae, Red Algae, Green Algae), Form (Solid, Liquid), Distribution Channel (Online, Offline), Application (Food and Beverages, Nutraceuticals and Dietary Supplements, Personal Care, Feed, Pharmaceuticals, Chemicals, and Others), and Region 2025-2033. https://www.imarcgroup.com/algae-products-market

Iversen, L., Winkel, A., Baastrup-Spohr, L., Hinke, A. B., Alahuhta, J., Baattrup-Pedersen, A., Birk, S., Brodersen, P., Chambers, P. & Ecke, F. (2019). Catchment properties and the photosynthetic trait composition of freshwater plant communities. Science 366(6467), 878–881. https://doi.org/10.1126/science.aay5945

Jacinto, M. L. J. A. J., David, C. P. C., Perez, T. R., De Jesus, B. R. (2009). Comparative efficiency of algal biofilters in the removal of chromium and copper from wastewater. Ecological Engineering 35, 856-860. https://doi.org/10.1016/j.ecoleng.2008.12.023

Jang, H. & Topal, E. (2020). Transformation of the Australian mining industry and future prospects. Mining Technology, 129(3), 120–134. https://doi.org/10.1080/25726668.2020.1786298

Jarvis, A. P. & Younger, P. L. (2000). Broadening the scope of mine water environmental impact assessment: a UK perspective. Environmental Impact Assessment Review 20, 85–96. https://doi.org/10.1016/S0195-9255(99)00032-3

Jassey, V. E. J., Walcker, R., Kardol, P., Geisen, S., Heger, T., Lamentowicz, M., Hamard, S. & Lara, E. (2022). Contribution of soil algae to the global carbon cycle. New Phytologist 234(1), 64–76. https://doi.org/10.1111/nph.17950

Jo, S.-W., Hong, J. W., Do, J.-M., Na, H., Kim, J.-J., Park, S.-I., Kim, Y.-S., Kim, I.-S. & Yoon, H.-S. (2020). Nitrogen deficiency-dependent abiotic stress enhances carotenoid production in indigenous green microalga *Scenedesmus rubescens* KNUA042, for use as a potential resource of high value products. Sustainability 12(13), 5445. https://doi.org/10.3390/su12135445

Johnson, D. B. (2015) Biomining goes underground. Nature Geoscience 8, 165-166. https://doi.org/10.1038/ngeo2384

Ju, X., Igarashi, K., Miyashita, S., Mitsuhashi, H., Inagaki, K., Fujii, S., Sawada, H., Kuwabara, T. & Minoda, A. (2016). Effective and selective recovery of gold and palladium ions from metal wastewater using a sulfothermophilic red alga, *Galdieria sulphuraria*. Bioresource Technology 211, 759–64. https://doi.org/10.1016/j.biortech.2016.01.061

Kaksonen, A. H. & Puhakka, J. A. (2007). Sulfate reduction based bioprocesses for the treatment of acid mine drainage and the recovery of metals. Engineering in Life Sciences 7(6), 541-564. https://doi.org/10.1002/elsc.200720216

Kaloudas, D., Pavlova, N. & Penchovsky, R. (2021). Phycoremediation of wastewater by microalgae: a review. Environmental Chemistry Letters 19(4), 2905-2920. https://doi.org/10.1007/s10311-021-01203-0

Karan, H., Roles, J., Hankamer, B. & Ross, I. L. (2023). Targeting greens and yellows: A solar biorefinery analysis for the microalgae-based co-production of pigments, proteins, and fuel. Algal Research 74, 103187. https://doi.org/10.1016/j.algal.2023.103187

Karan, H., Roles, J., Ross, I. L., Ebrahimi, M., Rackemann, D., Rainey T., & Hankamer, B. (2022). Solar biorefinery concept for sustainable co-production of microalgae-based protein and renewable fuel. Journal of Cleaner Production 368, 132981. https://doi.org/10.1016/j.jclepro.2022.132981

Katsoulas, N., Løes, A. K., Andrivon, D., Cirvilleri, G., de Cara, M., Kir, A., Knebl, L., Malińska, K., Oudshoorn, F. W., Willer, H. & Schmutz, U. (2020). Current use of copper, mineral oils and sulphur for plant protection in organic horticultural crops across 10 European countries. Organic Agriculture 10(S1), 159–171. https://doi.org/10.1007/s13165-020-00330-2

Keenan, J., & Holcombe, S. (2021). Mining as a temporary land use: A global stocktake of post-mining transitions and repurposing. Extractive Industries and Society 8(3), 100924. https://doi.org/10.1016/j.exis.2021.100924

Kesler, S. E., Gruber, P. W., Medina, P. A., Keoleian, G. A., Everson, M. P. & Wallington, T. J. (2012). Global lithium resources: Relative importance of pegmatite, brine and other deposits. Ore Geology Reviews 48, 55–69. https://doi.org/10.1016/j.oregeorev.2012.05.006

Ketchum, B. H. & Redfield, A. C. (1949). Some physical and chemical characteristics of algae growth in mass culture. Journal of Cellular and Comparative Physiology 33(3), 281–299. https://doi.org/10.1002/jcp.1030330303

Khan, Z., Elahi, A., Bukhari, D. A. & Rehman, A. (2022). Cadmium sources, toxicity, resistance and removal by microorganisms-A potential strategy for cadmium eradication. Journal of Saudi Chemical Society 26(6), 101569. https://doi.org/10.1016/j.jscs.2022.101569

Khan, M. I., Shin, J. H. & Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microbial Cell Factories 17(1), 1-21. https://doi.org/10.1186/s12934-018-0879-x

Khoubestani, R. S., Mirghaffari, N. & Farhadian, O. (2015). Removal of three and hexavalent chromium from aqueous solutions using a microalgae biomass-derived biosorbent. Environmental Progress & Sustainable Energy 34, 949-956. https://doi.org/10.1002/ep.12071

Klein, B. C., Davis, R. E. & Laurens, L. M. L. (2023). Quantifying the intrinsic value of algal biomass based on a multi-product biorefining strategy. Algal Research 72, 103094. https://doi.org/10.1016/j.algal.2023.103094

Koschorreck, M., Boehrer, B., Friese, K., Geller, W., Schultze, M. & Wendt-Potthoff, K. (2011). Oxygen depletion induced by adding whey to an enclosure in an acidic mine pit lake. Ecological Engineering 37(12), 1983-1989. https://doi.org/10.1016/j.ecoleng.2011.08.003

Koschorreck, M., Frommichen, R., Herzsprung, P., Tittel, J. & Wendt-Potthoff, K. (2002). Function of straw for in situ remediation of acidic mining lakes. Water, Air and Soil Pollution 2, 97–109. https://doi.org/10.1023/A:1019991326498

Krajcovic, J., Vesteg, M. & Schwartzbach, S. D. (2015). Euglenoid flagellates: A multifaceted biotechnology platform. Journal of Biotechnolology 202, 135-145. https://doi.org/10.1016/j.jbiotec.2014.11.035

Kruger, J. S., Wiatrowski, M., Davis, R. E., Dong, T., Knoshaug, E. P., Nagle, N. J., Laurens, L. M. L. & Pienkos, P. T. (2022). Enabling production of algal biofuels by techno-economic optimization of co-product suites. Frontiers in Chemical Engineering 3, 803513. https://doi.org/10.3389/fceng.2021.803513

Kumar, R. & Goyal, D. (2010). Waste water treatment and metal (Pb^{2+}, Zn^{2+}) removal by microalgal based stabilization pond system. Indian Journal of Microbiology 50, 34-40. https://doi.org/10.1007/s12088-010-0063-4

Kumar, R., Hegde, A. S., Sharma, K., Parmar, P. & Srivatsan, V. (2022). Microalgae as a sustainable source of edible proteins and bioactive peptides-Current trends and future prospects. Food Research International 157, 111338. https://doi.org/10.1016/j.foodres.2022.111338

Kumar, R. N., McCullough, C. D., Lund, M. A. & Larranaga, S. A. (2016). Assessment of factors limiting algal growth in acidic pit lakes–a case study from Western Australia, Australia. Environmental Science and Pollution Research 23(6), 5915–24. https://doi.org/10.1007/s11356-015-5829-0

Kumari, S. & Maiti, S. K. (2022). Nitrogen recovery in reclaimed mine soil under different amendment practices in tandem with legume and non-legume revegetation: A review. Soil Use and Management 38(2), 1113-1145. https://doi.org/10.1111/sum.12787

Lakaniemi, A.-M., Douglas, G. B. & Kaksonen, A. H. (2019). Engineering and kinetic aspects of bacterial uranium reduction for the remediation of uranium contaminated environments. Journal of Hazardous Materials 371, 198-212. https://doi.org/10.1016/j.jhazmat.2019.02.074

Larney, F. J. & Angers, D. A. (2012). The role of organic amendments in soil reclamation: a review. Canadian Journal of Soil Science 92, 19–38. https://doi.org/10.4141/cjss2010-064

Lavania, B., Azman, S., Mohd Said, M. I., Ahmad, F. & Mohamad, M. (2014). Biofiltration potential of macroalgae for ammonium removal in outdoor tank shrimp wastewater recirculation system. Biomass and Bioenergy 66, 103–109. https://doi.org/10.1016/j.biombioe.2014.02.031

Lavoie, A. & de la Noüe, J. (1985). Hyperconcentrated cultures of *Scenedesmus obliquus*: A new approach for wastewater biological tertiary treatment? Water Research 19(11), 1437-1442. https://doi.org/10.1016/0043-1354(85)90311-2

Lawton, R. J., Cole, A. J., Roberts, D. A., Paul, N. A. & de Nys, R. (2017). The industrial ecology of freshwater macroalgae for biomass applications. Algal Research 24, 486-491. https://doi.org/10.1016/j.algal.2016.08.019

Lee, A. K., Lewis, D. M. & Ashman, P. J. (2012) Disruption of microalgal cells for the extraction of lipids for biofuels: Processes and specific energy requirements. Biomass and Bioenergy 46, 89-101, https://doi.org/10.1016/j.biombioe.2012.06.034

Lengke, M. F., Ravel, B., Fleet, M. E., Wanger, G., Gordon, R. A. & Southam, G. (2006). Mechanisms of gold bioaccumulation by filamentous cyanobacteria from gold (iii)– chloride complex. Environmental Science & Technology 40(20), 6304–6309. https://doi.org/10.1021/es061040r

LePan, N. (2021). Visualizing the size of mine tailings. Real Assets. May 15, 2021. https://elements.visualcapitalist.com/visualizing-the-size-of-mine-tailings/

Lessmann, D., Fyson, A. & Nixdorf, B. (2000). Phytoplankton of the extremely acidic mining lakes of Lusatia (Germany) with pH ≤3. Hydrobiologia 433(1), 123–128. https://doi.org/10.1023/A:1004018722898

Levett, A., Gagen, E. J., Levett, I. & Erskine, P. D. (2023). Integrating microalgae production into mine closure plans. Journal of Environmental Management 337, 117736. https://doi.org/10.1016/j.jenvman.2023.117736

Li, T., Lin, G., Podola, B. & Melkonian, M. (2015). Continuous removal of zinc from wastewater and mine dump leachate by a microalgal biofilm PSBR. Journal of Hazardous Materials 297, 112-118. https://doi.org/10.1016/j.jhazmat.2015.04.080

Li, S., Hu, T., Xu, Y., Wang, J., Chu, R., Yin, Z., Mo, F. & Zhu, L. (2020). A review on flocculation as an efficient method to harvest energy microalgae: Mechanisms, performances, influencing factors and perspectives. Renewable and Sustainable Energy Reviews 131, 110005. https://doi.org/10.1016/j.rser.2020.110005

Li, Y. C., Xu, Z., Ma, H. Q. & Hursthouse, A. S. (2019). Removal of manganese (II) from acid mine wastewater: A review of the challenges and opportunities with special emphasis on Mn-oxidizing bacteria and microalgae. Water 11(12), 2493. https://doi.org/10.3390/w11122493

Liliana, C., Inga, Z., Ludmila, R., Tatiana, C., Ana, P., Andrei, A., Svetlana, D., Larisa, G. & Decebal, I. (2021). Biomass of *Arthrospira platensis* enriched with lithium by bioaccumulation and biosorption process. Food Bioscience 41, 100950. https://doi.org/10.1016/j.fbio.2021.100950

Liu, T. & Liu, S. (2020). The impacts of coal dust on miners' health: A review. Environmental Research 190, 109849. https://doi.org/10.1016/j.envres.2020.109849

López-Archilla, A. I., Marín, I. & Amils, R. (2001). Microbial community composition and ecology of an acidic aquatic environment: the Tinto River, Spain. Microbial Ecology 41, 20–35. https://doi.org/10.1007/s002480000044

López Rocha, C. J., Álvarez-Castillo, E., Estrada Yáñez, M. R., Bengoechea, C., Guerrero, A., Orta Ledesma, M. T. (2020). Development of bioplastics from a microalgae consortium from wastewater. Journal of Environmental Management 263, 110353. https://doi.org/10.1016/j.jenvman.2020.110353

Lucheta, A. R., Otero, X. L., Macias, F. & Lambais, M. R. (2013). Bacterial and archaeal communities in the acid pit lake sediments of a chalcopyrite mine. Extremophiles 17(6):941–951. https://doi.org/10.1007/s00792-013-0576-y

Lund, M. A. & Blanchette, M. L. (2021). C27043 Towards closure of potentially saline pit lakes: understanding biophysical processes for condition assessment and remediation options. Mine Water and Environment Research Centre Report No. 2020-03, Edith Cowan University, Perth, Australia. 110 pp. Report to the Australian Coal Association Research Program.

Machado, L., Kinley, R. D., Magnusson, M., de Nys, R. & Tomkins, N. W. (2014). The potential of macroalgae for beef production systems in Northern Australia. Journal of Applied Phycology 27(5), 2001–2005. https://doi.org/10.1007/s10811-014-0439-7

Madeira, M. S., Cardoso, C., Lopes, P. A., Coelho, D., Afonso, C., Bandarra, N. M. & Prates, J. A. M., 2017. Microalgae as feed ingredients for livestock production and meat quality: A review. Livestock Science 205, 111-121. https://doi.org/10.1016/j.livsci.2017.09.020

Maithani, D., Dasila, H., Saxena, R., Tiwari, A., Bhatt, D., Rawat, K. & Suyal, D. C. (2023). Heavy Metal Pollution in Water: Cause and Remediation Strategies. In: Soni, R., Suyal, D. C., Morales-Oyervides, L. & Sungh Chauhan, J. (Eds.), Current Status of Fresh Water Microbiology. Springer, Singapore. Pp. 181–204. Springer. https://doi.org/10.1007/978-981-99-5018-8_8

Mandal, S., Nagi, G. K., Corcoran, A. A., Agrawal, R., Dubey, M. & Hunt, R. W. (2023). Algal polysaccharides for 3d printing: A review. Carbohydrate Polymers 300, 120267. https://doi.org/10.1016/j.carbpol.2022.120267

Manero, A., Kragt, M., Standish, R., Miller, B., Jasper, D., Boggs, G. & Young, R. (2020). A framework for developing completion criteria for mine closure and rehabilitation. Journal of Environmental Management 273, 111078. https://doi.org/10.1016/j.jenvman.2020.111078

Markets and Markets (2024a). Algae products market overview 2028. https://www.marketsandmarkets.com/Market-Reports/algae-product-market-250538721.html

Markets and Markets (2024b). Biostimulants Market. https://www.marketsandmarkets.com/Market-Reports/biostimulant-market-1081.html

Markets and Markets (2024c). Lutein Market. https://www.marketsandmarkets.com/Market-Reports/lutein-market-69753879.html

Markets and Markets (2024d). Polyhydroxyalkanoate (PHA) Market by Type, Production Methods, Application, and Region - Global Forecast to 2028. https://www.marketsandmarkets.com/Market-Reports/pha-market-395.html

Martínez-Macias, M. d. R., Correa-Murrieta, M. A., Villegas-Peralta, Y., Dévora-Isiordia, G. E., Alvarez Sánchez, J., Saldivar-Cabrales, J. & Sánchez-Duarte, R. G. (2019). Uptake of copper from acid mine drainage by the microalgae *Nannochloropsis oculata*. Environmental Science and Pollution Research 26(7), 6311–6318. https://doi.org/10.1007/s11356-018-3963-1

Mathiyazhagan, N. (2011). Bioremediation on effluents from magnesite and bauxite mines using *Thiobacillus* spp. and *Pseudomonas* spp. Journal of Bioremediation & Biodegradation 2, 115. https://doi.org/10.4172/2155-6199.1000115

Maybee, B., Boggs, G., Stevens, R. & Scrase, A. (2024). Who is responsible for the residual risk and how can it be shared or transferred to optimize post-mine outcomes? Research Directions: Mine Closure and Transitions 1, e6. https://doi.org/10.1017/mcl.2024.2

McCullough, C. D., Schultze, M. & Vandenberg, J. A. (2020). Realizing beneficial end uses from abandoned pit lakes. Minerals 10(2), 133. https://doi.org/10.3390/min10020133

McNamara, K. & Awramik, S. (1992). Stromatolites: a key to understanding the early evolution of life. Science Progress (1933-), pages 345–364.

Measham, T., Walker, J., McKenzie, F. H., Kirby, J., Williams, C., D'Urso, J., Littleboy, A., Sampler, A., Rey, R., Maybee, B., Breton, D. & Boggs, G. (2024). Beyond closure: A literature review and research agenda for post-mining transitions. Resources Policy, 0, 104859. https://doi.org/10.1016/j.resourpol.2024.104859

Mehta, S. K. & Gaur, J. P. (2005). Use of algae for removing heavy metal ions from wastewater: progress and prospects. Critical Reviews in Biotechnology 25, 113e152. https://doi.org/10.1080/07388550500248571

Meng, F., McNeice, J., Zadeh, S. S. & Ghahreman, A. (2019). Review of lithium production and recovery from minerals, brines, and lithium ion batteries. Mineral Processing and Extractive Metallurgy Review 42(2), 123–141. https://doi.org/10.1080/08827508.2019.1668387

Mhatre, A., Navale, M., Trivedi, N., Pandit, R. & Lali, A. M. (2018). Pilot scale flat panel photobioreactor system for mass production of *Ulva lactuca* (Chlorophyta). Bioresource Technology 249, 582-91. https://doi.org/10.1016/j.biortech.2017.10.058

Millar, A. (2009). Macroalgae. Factsheet, New South Wales Department of Industry and Investment. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/378774/Macroalgae-Primefact-947.pdf

Minerals Council of Australia (MCA). (2021). First Nations partnerships, MCA, Canberra, https://www.minerals.org.au/first-nations-partnerships.

Moheimani, N. R. & Borowitzka, M. A. (2011). Increased CO_2 and the effect of pH on growth and calcification of *Pleurochrysis carterae* and *Emiliania huxleyi* (haptophyta) in semicontinuous cultures. Applied Microbiology and Biotechnology 90(4), 1399–1407. https://doi.org/10.1007/s00253-011-3174-x

Molina, E., Fernández, J., Acién, F. G. & Chisti, Y. (2001). Tubular photobioreactor design for algal cultures, Journal of Biotechnology 92, 113-131. https://doi.org/10.1016/S0168-1656(01)00353-4

Molwantwa, J. B., Molipane, N. P. & Rose, P. D. (2000). Biological sulphate reduction utilizing algal extracellular products as a carbon source. In: WISA 2000 Biennial Conference, Sun City, South Africa, 28 May to 1 June 2000. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjdt73n6ouKAxWHzDgGHSlJAQ0QFnoECBoQAQ&url=https%3A%2F%2Fwisa.org.za%2Fwp-content%2Fuploads%2F2018%2F12%2FWISA2000-P123.pdf&usg=AOvVaw0wjvghBuG0Y8JgZXWLrV6d&opi=89978449

Moore, B. (2023). NAB Carbon Research: ACCU prices set to soar. Business Research and Insights. https://business.nab.com.au/nab-carbon-research-accu-prices-set-tp-57768/

Moser, M. & Weisse, T. (2011). Combined stress effect of pH and temperature narrows the niche width of flagellates in acid mining lakes. Journal of Plankton Research 33(7), 1023–1032. https://doi.org/10.1093/plankt/fbr014

Mucsi, G., Halyag, N., Kurusta, T. & Kristály, F. (2021). Control of carbon dioxide sequestration by mechanical activation of red mud. Waste and Biomass Valorization 12(12), 6481–6495. https://doi.org/10.1007/s12649-021-01466-2

Mudd, G. M. (2007). Gold mining in Australia: linking historical trends and environmental and resource sustainability. Environmental Science & Policy 10(7-8), 629–644. https://doi.org/10.1016/j.envsci.2007.04.006

Mujtaba, G., Rizwan, M., Kim, G. & Lee, K. (2018) Removal of nutrients and COD through co-culturing activated sludge and immobilized *Chlorella vulgaris*. Chemical Engineering Journal 343, 155–162. https://doi.org/10.1016/j.cej.2018.03.007

Mulders, K. J. M. (2014) Phototrophic pigment production with microalgae. PhD Thesis. Wageningen University. https://edepot.wur.nl/323615

Munir, N., Imtiaz, A., Sharif, N. & Naz, S. (2015). Optimization of growth conditions of different algal strains and determination of their lipid contents. JAPS: Journal of Animal & Plant Sciences 25(2), 546-553. https://www.thejaps.org.pk/docs/v-25-02/30.pdf

Muñoz, R. & Guieysse, B. (2006). Algal–bacterial processes for the treatment of hazardous contaminants: a review. Water Research 40, 2799-2815. https://doi.org/10.1016/j.watres.2006.06.011

Mustafa, A., Athirah, A., Ratnawati, E., Paena, M., Kamariah, K., Asaad, A. I. J., Tarunamulia, T., Asaf, R., Syaichudin, M. & Taukhid, I. (2024). Identifying the environmental factors that determine the agar content of seaweed *Gracilaria verrucosa* in acid sulfate soil-affected brackishwater ponds. Polish Journal of Environmental Studies 33(4), pp.4673-4686. https://doi.org/10.15244/pjoes/178449

Nad, M., Brummer, V., Lošák, P., Máša, V., Sukačová, K., Tatarová, D., Pernica, M. & Procházková, M. (2023). Waste-to-energy plants flue gas CO_2 mitigation using a novel tubular photobioreactor while producing Chlorella algae. Journal of Cleaner Production 385, 135721. https://doi.org/10.1016/j.jclepro.2022.135721

Nagarajan, D., Leea, D.-J., Varjani, S., Lame, S. S., Allakhverdiev, S. I. & Chang, J.-S. (2022). Microalgae-based wastewater treatment – Microalgae-bacteria consortia, multi-omics approaches and algal stress response. Science of the Total Environment 845, 157110. https://doi.org/10.1016/j.scitotenv.2022.157110

Náhlík, V., Čížková, M., Singh, A., Bišová, K., Mezrický, D., Rucký, M. & Vítová, M. (2021). Red mud as a secondary source of scarce metals - recovery using red microalgae. 17th International Conference on Environmental Science and Technology, Athens Greece. https://cms.gnest.org/sites/default/files/Proceedings/cest2021_00027/cest2021_00027.pdf

Naidu, G., Ryu, S., Thiruvenkatachari, R., Choi, Y., Jeong, S. & Vigneswaran, S. (2019). A critical review on remediation, reuse, and resource recovery from acid mine drainage. Environmental Pollution 247, 1110–1124. https://doi.org/10.1016/j.envpol.2019.01.085

Nancucheo, I. & Johnson, B. D. (2012). Acidophilic algae isolated from mine-impacted environments and their roles in sustaining heterotrophic acidophiles. Frontiers in Microbiology 3, 325. https://doi.org/10.3389/fmicb.2012.00325

Narayanan, M., Devarajan, N., He, Z., Kandasamy, S., Ashokkumar, V., Raja, R. & Carvalho, I. S. (2020). Assessment of microbial diversity and enumeration of metal tolerant autochthonous bacteria from tailings of magnesite and bauxite mines. Materials Today: Proceedings, 33, 4391– 4401. https://doi.org/10.1016/j.matpr.2020.07.652

Neculita, C. M., Demers, I. & Braghiroli, F. L. (2024): Performance of natural and residual materials for mine water treatment and mine sites rehabilitation. In: Kleinmann, B., Skousen, J. & Wolkersdorfer, Ch.: West Virginia Mine Drainage Task Force Symposium & 15th International Mine Water Association Congress. Morgantown, WV, USA (International Mine Water Association). Pp. 487 – 493. https://www.imwa.info/docs/imwa_2024/IMWA2024_Neculita_487.pdf

Nordstrom, D. K., Alpers, C. N., Ptacek, C. J. & Blowes, D. W. (2000). Negative pH and extremely acidic mine waters from Iron Mountain, California. Environmental Science & Technology 34(2), 254-258. doi.org/10.1021/es990646v

Nordstrom, D. K., Blowes, D. W. & Ptacek, C. J. (2015). Hydrogeochemistry and microbiology of mine drainage: An update. Applied Geochemistry 57, 3-16. doi.org/10.1016/j.apgeochem.2015.02.008.

Noreen, A., Zia, K. M., Zuber, M., Ali, M. & Mujahid, M. (2016). A critical review of algal biomass: a versatile platform of bio-based polyesters from renewable resources. International Journal of Biological Macromolecules 86, 937–949. https://doi.org/10.1016/j.ijbiomac.2016.01.067

Northern Land Council (NLC). (2021). Mining exploration and production, NLC, Darwin, www.nlc.org.au/building-the-bush/mining-and-minerals.

Northern Territory of Australia, Department of Lands, Planning and Environment (1998). Waste Management and Pollution Control (WMPC) Regulations 1998. https://legislation.nt.gov.au/Legislation/WASTE-MANAGEMENT-AND-POLLUTION-CONTROL-ACT-1998

Northey, S., Haque, N. & Mudd, G. (2013). Using sustainability reporting to assess the environmental footprint of copper mining. Journal of Cleaner Production 40, 118-128. http://dx.doi.org/10.1016/j.jclepro.2012.09.027.

Novis, P. M. (2019). Taxonomy of *Klebsormidium* (Klebsormidiales, Charophyceae) in New Zealand streams and the significance of low-pH habitats. Phycologia 45(3), 293–301. https://doi.org/10.2216/04-70.1

Novis, P. M. & Harding, J. S., 2007. Extreme Acidophiles: Freshwater Algae Associated with Acid Mine Drainage. In: Seckbach, J. (Ed.), Algae and Cyanobacteria in Extreme Environment. Springer, The Netherlands. pp. 443-463.

Novoveska, L., Nielsen, S. L., Eroldogan, O. T., Haznedaroglu, B. Z., Rinkevich, B., Fazi, S., Robbens, J., Vasquez, M. & Einarsson, H. (2023). Overview and challenges of large-scale cultivation of photosynthetic microalgae and cyanobacteria. Marine Drugs 21(8), 445. https://doi.org/10.3390/md21080445

Nwoba, E. G., Ayre, J. M., Moheimani, N. R., Ubi, B. E. & Ogbonna J. C. (2016). Growth comparison of microalgae in tubular photobioreactor and open pond for treating anaerobic digestion piggery effluent. Algal Research 17, 268-76. https://doi.org/10.1016/j.algal.2016.05.022

Nwoba, E. G., Parlevliet, D. A., Laird, D. W., Alameh, K. & Moheimani, N. R. (2020). Pilot-scale self-cooling microalgal closed photobioreactor for biomass production and electricity generation. Algal Research 45, 101731. https://doi.org/10.1016/j.algal.2019.101731

Oberholster, P. J., Cheng, P.-H., Botha, A.-M. & Genthe, B. (2014). The potential of selected macroalgal species for treatment of AMD at different pH ranges in temperate regions. Water Research 60, 82–92. https://doi.org/10.1016/j.watres.2014.04.031

Oberholster, P. J., Cheng, P.-H., Botha, A.-M., Hobbs, P. & Hill, L. (2018). Assessment of selected macroalgae for use in a biological hybrid system for treating sulphur in acid mine drainage (AMD). Journal of applied phycology 30, 1361-1370. https://doi.org/10.1007/s10811-017-1314-0

Office of the Queensland Mine Rehabilitation Commissioner (2024). Queensland Mine Rehabilitation Commissioner 2023-2024 report. https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0029/357374/qmrc-2023-24-annual-report.pdf

Olaueson, M. M. & Stokes, P. M. (1989). Responses of the acidophilic alga *Euglena mutabilis* (Euglenophyceae) to carbon enrichment at pH 3. Journal of Phycology 25(3), 529–539. https://doi.org/10.1111/j.1529-8817.1989.tb00259.x

Olem, H. & Unz, R. F. (1980). Rotating disc biological treatment of acid mine drainage. Journal (Water Pollution Control Federation) 52(2), 257-269.

Oliver, L., Fernández-de-Castro, L., Dietrich, T., Villaran, M. C. & Barrio, R. J. (2022). Production of docosahexaenoic acid and odd-chain fatty acids by microalgae grown on waste-derived volatile fatty acids. Applied Sciences 12(8), 3976. https://doi.org/10.3390/app12083976

Olivieri, G., Marzocchella, A., Andreozzi, R., Pinto, G. & Pollio, A. (2011). Biodiesel production from *Stichococcus* strains at laboratory scale. Journal of Chemical Technology & Biotechnology 86(6), 776–783. https://doi.org/10.1002/jctb.2586

Onyeaka, H., Miri, T., Obileke, K., Hart, A., Anumudu, C. & Al-Sharify, Z. T. (2021). Minimizing carbon footprint via microalgae as a biological capture. Carbon Capture Science & Technology 1, 100007. https://doi.org/10.1016/j.ccst.2021.100007.

Orandi, S. & Lewis, D. M. (2012). Synthesising acid mine drainage to maintain and exploit indigenous mining micro-algae and microbial assemblies for biotreatment investigations. Environmental Science and Pollution Research 20(2), 950–956. https://doi.org/10.1007/s11356-012-1006-x

Orandi, S. & Lewis, D. M. (2013). Biosorption of heavy metals in a photorotating biological contactor—a batch process study. Applied Microbiology and Biotechnology 97(11), 5113–5123. https://doi.org/10.1007/s00253-012-4316-5

Orandi, S., Lewis, D. M. & Moheimani, N. R. (2012). Biofilm establishment and heavy metal removal capacity of an indigenous mining algal-microbial consortium in a photo-rotating biological contactor. Journal of Industrial Microbiology and Biotechnology 39(9), 1321–31. https://doi.org/10.1007/s10295-012-1142-9

Orandi, S., Yaghubpur, A., Sahraei, H. & Behrouz, M. (2007). Influence of acid mine drainage on aquatic life at Sar Cheshmeh copper mine. Geochimica et Cosmochimica Acta 71(15) Supplement 742. https://goldschmidtabstracts.info/abstracts/abstractView?id=2007005197

Palma, H., Killoran, E., Sheehan, M., Berner, F. & Heimann, K. (2017). Assessment of microalga biofilms for simultaneous remediation and biofuel generation in mine tailings water. Bioresource Technology 234, 327-335. https://doi.org/10.1016/j.biortech.2017.03.063

Pálmai, T., Szabó, B., Kotut, K., Krienitz, L. & Padisák, J. (2020). Ecophysiology of a successful phytoplankton competitor in the African flamingo lakes: the green alga *Picocystis salinarum* (Picocystophyceae). Journal of Applied Phycology 32(3), 1813–1825. https://doi.org/10.1007/s10811-020-02092-6

Panis, G. & Carreon, J. R. (2016). Commercial astaxanthin production derived by green alga *Haematococcus pluvialis*: A microalgae process model and a techno-economic assessment all through production line. Algal Research 18, 175–190. https://doi.org/10.1016/j.algal.2016.06.007

Paramasivam, P., Kanagesan, K., Bhuyar, P., Govindan, N., Ab Rahim, M. H. & Maniam, G. P. (2021). Biomass and lipid production from indigenous *Nannochloropsis* sp. by employing stress factors for improved biodiesel production. Environment, Development and Sustainability 1-15. https://doi.org/10.1007/s10668-021-01910-2

Park, J. B. K., Craggs, R. J. & Shilton, A. N. (2011). Wastewater treatment high rate algal ponds for biofuel production. Bioresource Technology 102(1), 35-42. https://doi.org/10.1016/j.biortech.2010.06.158

Park, Y.-T., Lee, H., Yun, H.-S., Song, K.-G., Yeom, S.-H. & Choi, J. (2013). Removal of metal from acid mine drainage using a hybrid system including a pipes inserted microalgae reactor. Bioresource Technology 150, 242-248. https://doi.org/10.1016/j.biortech.2013.09.136

Pawlik-Skowronska, B. (2001). Phytochelatin production in freshwater algae *Stigeoclonium* in response to heavy metals contain in mining water, effects of some environmental factors. Aquatic Toxicology 52, 241-249. https://doi.org/10.1016/S0166-445X(00)00144-2

Pedrol, N., Puig, C. G., Souza, P., Forján, R., Vega, F. A., Asensio, V., González, L., Cerqueira, B., Covelo, E. F. & Andrade, L. (2010). Soil fertility and spontaneous revegetation in lignite spoil banks under different amendments. Soil and Tillage Research 110(1), 134-142. https://doi.org/10.1016/j.still.2010.07.005

Pérez-Roa, M. E., Ortiz-Alvarez, M. D., García-Martínez, J. B., Barajas-Solano, A. F. & Barajas-Solano, C. (2024). Use of mining effluents for the production of algal-based colorants. Ingenieria Y Competitividad 26(3), e-20313752. https://doi.org/10.25100/iyc.v26i3.13752

Perlatti, F. & Gagen, E. J. (2024). What emerging technologies and innovations present opportunities for economic repurposing of mined land, assets, and waste materials?. Research Directions: Mine Closure and Transitions 1, e1, 1-2. https://doi.org/10.1017/mcl.2023.4

Persistence Market Research (2024). Algae-Based Animal Feed Market. Persistence Market Research. 2024. https://www.persistencemarketresearch.com/market-research/algae-based-animal-feed-market.asp

Phillips, P., Bender, J., Simms, R., Rodriguez-Eaton, S. & Britt, C. (1995). Manganese removal from acid coal-mine drainage by a pond containing green algae and microbial mat. Water Science & Technology 31(12), 161-170. https://doi.org/10.1016/0273-1223(95)00503-F

Pinto, J., Henriques, B., Soares, J., Costa, M., Dias, M., Fabre, E., Lopes, C. B., Vale, C., Pinheiro-Torres, J. & Pereira, E. (2020) A green method based on living macroalgae for the removal of rare-earth elements from contaminated waters. Journal of Environmental Management 263, 110376, https://doi.org/10.1016/j.jenvman.2020.110376

Pirouzi, A., Nosrati, M., Shojaosadati, S. A. & Shakhesi, S. (2014). Improvement of mixing time, mass transfer, and power consumption in an external loop airlift photobioreactor for microalgae cultures. Biochemical Engineering Journal, 87, 25-32. https://doi.org/10.1016/j.bej.2014.03.012

Plante, B., Schudel, G. & Benzaazoua, M. (2021). Generation of Acid Mine Drainage. In: Bussière, B., Guittonny, M. (Eds.) Hard Rock Miene Reclamation. From Prediction to Management of Acid Mine Drainage. CRC Press, Boca Raton. 1st Edition. Pp. 1–20. https://doi.org/10.1201/9781315166698

Plumlee, G. S. (1999). The Environmental Geology of Mineral Deposits. In: Plumlee, G. S., Logsdon, M. J. (Eds.), The Environmental Geochemistry of Mineral Deposits, Part A: Processes, Techniques and Health Issues, Reviews in Economic Geology Vol. 6A, Society of Economic Geologists, Inc. Pp. 71-116.

Prasanna, R., Ratha, S. K., Rojas, C. & Bruns, M. A. (2011). Algal diversity in flowing waters at an acidic mine drainage “barrens” in central Pennsylvania, USA. Folia Microbiologica 56(6), 491–496. https://doi.org/10.1007/s12223-011-0073-6

Punia, A. (2019). Innovative and sustainable approach for phytoremediation of mine tailings: a review. Waste Disposal & Sustainable Energy 1(3), 169-176. https://doi.org/10.1007/s42768-019-00022-y

Queensland Government (1989). Mineral Resources Act 1989. https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-1989-110

Queensland Government (1993). Native Title Act (Queensland) 1993. https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-1993-085

Queensland Government (1994). Environmental Protection Act 1994. https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-1994-062

Queensland Government (1999). Coal Mining Safety and Health Act 1999. https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-1999-039

Queensland Government (2011). Waste Reduction and Recycling Act 2011. https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2011-031

Queensland Government (2014). Biosecurity Act 2014. https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2014-007

Queensland Government (2018). Environmental Protection (Waste ERA Framework) Amendment Regulation 2018. https://www.legislation.qld.gov.au/view/pdf/asmade/sl-2018-0198

Queensland Government (2019). Environmental Protection Regulation (2019). https://www.legislation.qld.gov.au/view/pdf/inforce/2022-03-11/sl-2019-0155

Queensland Government (2024). Progressive rehabilitation and closure plan for mined land. https://www.business.qld.gov.au/running-business/environment/licences-permits/rehabilitation/progressive-rehabilitation-closure-plans

Queensland Treasury (2021). Financial Provisioning Scheme Annual Report 2020-2021. The State of Queensland, Queensland Treasury.

Qureshi, A., Maurice, C. & Ohlander, B. (2016). Potential of coal mine waste rock for generating acid mine drainage. Journal of Geochemical Exploration 160, 44–54. doi.org/10.1016/j.gexplo.2015.10.014

Rafiqul, I. M., Jalal, K. C. A. & Alam, M. Z. (2005). Environmental factors for optimisation of *Spirulina* biomass in laboratory culture. Biotechnology 4, 19-22. https://doi.org/10.3923/biotech.2005.19.22

Rajesh Banu, J., Preethi, Kavitha, S., Gunasekaran, M. & Kumar, G. (2020). Microalgae based biorefinery promoting circular bioeconomy-techno economic and life-cycle analysis. Bioresource Technology 302, 122822. https://doi.org/10.1016/j.biortech.2020.122822

Rajpoot, A. S., Choudhary, T., Chelladurai, H., Verma, T. N. & Shende, V. (2022). A comprehensive review on bioplastic production from microalgae. Materials Today Proceedings 56(1), 171–178. https://doi.org/10.1016/j.matpr.2022.01.060

Rakotonimaro, T. V., Guittony, M. & Neculita, C. M. (2021). Compaction of peat cover over desulfurized gold mine tailings changes: Arsenic speciation and mobility. Applied Geochemistry 128, 104923. https://doi.org/10.1016/j.apgeochem.2021.104923

Rankic, I., Zelinka, R., Ridoskova, A., Gagic, M., Pelcova, P. & Huska, D. (2021). Nano/microparticles in conjunction with microalgae extract as novel insecticides against mealworm beetles, *Tenebrio molitor.* Scientific Reports 11(1),17125. https://doi.org/10.1038/s41598-021-96426-0

Rao, N. R. H. & Henderson, R. K. (2022). *9* - Unit Operations Applied for Microalgae-Based Solid–Liquid Separation. In: Jacob-Lopes, E., Zepka, L. Q., Severo, I. A., Maroneze, M. M. (Eds.) Woodhead Publishing Series in Energy, 3rd Generation Biofuels, Woodhead Publishing. Pp. 175–212. https://doi.org/10.1016/B978-0-323-90971-6.00015-2

Rasul, F., You, D., Jiang, Y., Liu, X. & Daroch, M. (2024). Thermophilic cyanobacteria-exciting, yet challenging biotechnological chassis. Applied Microbiology and Biotechnology 108(1), 270. https://doi.org/10.1007/s00253-024-13082-w

Rawat, S., Gangwar, A. & Kumar, S. (2024). Semi-continuous cultivation of microalgae to treat coal mine effluent in pilot scale: Nutrient removal, biodesalination and fatty acid composition analysis. Journal of Water Process Engineering 67, 106271. https://doi.org/10.1016/j.jwpe.2024.106271

Ray, N. E., Terlizzi, D. E. & Kangas, P. C. (2015). Nitrogen and phosphorus removal by the Algal Turf Scrubber at an oyster aquaculture facility. Ecological Engineering 78, 27-32. https://doi.org/10.1016/j.ecoleng.2014.04.028

Reavie, E. & Smol, J. (2001). Diatom-environmental relationships in 64 alkaline Southeastern Ontario (Canada) lakes: a diatom-based model for water quality reconstructions. Journal of Paleolimnology 25, 25–42. https://doi.org/10.1023/A:1008123613298

Redfield, A. C. (1934). On the proportions of organic derivatives in sea water and their relation to the composition of plankton. James Johnstone Memorial Volume. Pp. 176–192.

Rehman, A. & Shakoori, A. (2004). Tolerance and uptake of cadmium and nickel by *Chlorella* sp., isolated from tannery effluents. Pakistan Journal of Zoology 36(4), 327–331.

Reisoglu, Ş. & Aydin, S. (2023). Microalgae as a Promising Candidate for Fighting Climate Change and Biodiversity Loss. In: Aydin, S. (Ed.) Microalgae – Current and Potential Applications. IntechOpen, London. Pp. 1-26. https://doi.org/10.5772/intechopen.1002414

Research and Markets (2023a). Global Beta-Carotene (Natural, Synthetic) Market Analysis Report 2023: A $530+ Million Industry by 2030 - Natural and Sustainable Algae-Based Beta-Carotene Leads the Way. https://finance.yahoo.com/news/global-beta-carotene-natural-synthetic-144300200.html?guccounter=1

Research and Markets (2023b). Global Beta-Carotene (Natural, Synthetic) Market Analysis Report 2023: A $530+ Million Industry by 2030 - Natural and Sustainable Algae-Based Beta-Carotene Leads the Way. October 4, 2023. https://finance.yahoo.com/news/global-beta-carotene-natural-synthetic-144300200.html

Research and Markets (2024). Beta-Carotene Market Size, Competitors & Forecast to 2030. https://www.researchandmarkets.com/report/natural-beta-carotene

Research Nester (2024a). Alginates Market Size & Share, Forecast Report 2036. Research Nester. June 28, 2024. https://www.researchnester.com/reports/alginates-market/4051

Research Nester (2024b). Blue-Green Algae (BGA) Fertilizer Market Forecast Report 2024-2036. Research Nester. July 23, 2024. https://www.researchnester.com/reports/blue-green-algae-bga-fertilizer-market/3362

Research Nester (2024c). Nanocellulose Market Size & Share, Global Forecast Report 2037. Research Nester. October 10, 2024. https://www.researchnester.com/reports/nanocellulose-market/3576

Rey, N. J., Demers, I., Bussière, B., Mbonimpa, M. & Gagnon, M. (2020). A geochemical evaluation of a monolayer cover with an elevated water table for the reclamation of the Doyon-Westwood tailings ponds, Canada. Environmental Earth Sciences 79, 58. https://doi.org/10.1007/s12665-019-8797-8

Ribet, I., Ptacek, C. J., Blowes, D. W. & Jambor, J. L. (1995). The potential for metal release by reductive dissolution of weathered mine tailings. Journal of Contaminant Hydrology 17(3), 239-273. https://doi.org/10.1016/0169-7722(94)00010-f

Rito-Palomares, M., Nuñez, L. & Amador, D. (2001). Practical application of aqueous two-phase systems for the development of a prototype process for c-phycocyanin recovery from *Spirulina maxima*: Aqueous two-phase process for recovery of c-phycocyanin. Journal of Chemical Technology and Biotechnology 76(12), 1273–1280. https://doi.org/10.1002/jctb.507

Robb, G. A. (1994) Environmental consequences of coal mine closure. Geographical Journal 160, 33-40. doi.org/10.2307/3060139.

Roberts, D. A., Cole, A. J., Paul, N. A. & de Nys, R. (2015a). Algal biochar enhances the re-vegetation of stockpiled mine soils with native grass. Journal of Environmental Management 161, 173-180. https://doi.org/10.1016/j.jenvman.2015.07.002

Roberts, D. A., Paul, N. A., Cole, A. J. & de Nys, R. (2015b). From waste water treatment to land management: conversion of biomass to biochar for soil amelioration and the fortification of crops with essential trace elements. Journal of Environmental Management 157, 60-68. https://doi.org/10.1016/j.jenvman.2015.04.016

Roche, C. & Judd, S. (2016). Ground truths: taking responsibility for Australia's mining legacies. Mineral Policy Institute, Australia. https://www.mpi.org.au/wp-content/uploads/2016/06/Ground-Truths-2016-web.pdf

Rocher-Rivas, R., González-Sánchez, A., Ulloa-Mercado, G., Munõz, R. & Quijano, G. (2022). Biogas desulfurization and calorific value enhancement in compact H_2S/CO_2 absorption units coupled to a photobioreactor. Journal of Environmental Chemical Engineering 10(5), 108336. https://doi.org/10.1016/j.jece.2022.108336

Roesler, C. S., Culbertson, C. W., Etheridge, S. M., Goericke, R., Kiene, R. P., Miller, L. G. & Oremland, R. S. (2002). Distribution, production, and ecophysiology of *Picocystis* strain ML in Mono lake, California. Limnology and Oceanography 47(2), 440–452. https://doi.org/10.4319/lo.2002.47.2.0440

Roles, J., Yarnold, J., Hussey, K. & Hankamer, B. (2021). Techno-economic evaluation of microalgae high-density liquid fuel production at 12 international locations. Biotechnology for Biofuels 14, 133. https://doi.org/10.1186/s13068-021-01972-4.

Rose, P. D., Boshoff, G. A., van Hille, R. P., Wallace, L. C. M., Dunn, K. M. & Duncan, J. R. (1998). An integrated algal sulphate reducing high rate ponding process for the treatment of acid mine drainage wastewaters. Biodegradation 9(3-4), 247-257. https://doi.org/10.1023/A:1008352008353

Ross, I. L., Shah, S., Hankamer, B. & Amiralian, N. (2021). Microalgal nanocellulose - opportunities for a circular bioeconomy. Trends in Plant Science 26(9), 924–939. https://doi.org/10.1016/j.tplants.2021.05.004

Ruiz, J., Olivieri, G., de Vree, J., Bosma, R., Willems, P., Reith, J. H., Eppink, M. H. M., Kleinegris, D. M. M., Wijffels, R. H. & Barbosa, M. J. (2016). Towards industrial products from microalgae. Energy & Environmental Science 9(10), 3036–3043. https://doi.org/10.1039/C6EE01493C

Rupawalla, Z., Robinson, N., Schmidt, S., Li, S., Carruthers, S., Buisset, E., Roles, J., Hankamer, B. & Wolf, J. (2021). Algae biofertilisers promote sustainable food production and a circular nutrient economy – An integrated empirical-modelling study. Science of The Total Environment 796, 148913, https://doi.org/10.1016/j.scitotenv.2021.148913

Rupawalla, Z., Shaw, L., Ross, I. L., Schmidt, S., Hankamer, B. & Wolf, J. (2022). Germination screen for microalgae-generated plant growth biostimulants. Algal Research 66, 102784. https://doi.org/10.1016/j.algal.2022.102784

Rybak, A. S. (2018). Species of *Ulva* (Ulvophyceae, Chlorophyta) as indicators of salinity. Ecological Indicators 85, 253-61. https://doi.org/10.1016/j.ecolind.2017.10.061

Ryther, J. H., DeBusk, T. A. & Blakeslee, M. (1984). Cultivation and conversion of marine macroalgae [*Gracilaria* and *Ulva*]. Technical report by Harbor Branch Foundation, Fort Pierce, FL (USA). U.S. for the Department of Energy Office of Scientific and Technical Information. https://doi.org/10.2172/6711668

Saavedra, R., Munõoz, R., Taboada, M. E., Vega, M. & Bolado, S. (2018). Comparative uptake study of arsenic, boron, copper, manganese and zinc from water by different green microalgae. Bioresource Technology 263, 49– 57. https://doi.org/10.1016/j.biortech.2018.04.101

Sabathini, H. A., Windiani, L., Dianursanti, Gozan, M., Kusrini, E., Juwono, F. H., Yatim, A. & Setiawan, E. A. (2018). Mechanical physical properties of *Chlorella*-PVA based bioplastic with ultrasonic homogenizer. E3S Web of Conferences 67, 3046. https://doi.org/10.1051/e3sconf/20186703046

Safafar, H., Norregaard, P. U., Ljubic, A., Moller, P., Holdt, S. L. & Jacobsen, C. (2016). Enhancement of protein and pigment content in two species cultivated on industrial process water. Journal of Marine Science and Engineering 4(4), 84. https://doi.org/10.3390/jmse4040084

Sahinkaya, E., Ucar, D. & Kaksonen, A. H. (2017). Bioprecipitation of Metals and Metalloids. In: Lens, P., Rene, E., Lewis, A. & Sahinkaya, E. (Eds). Sustainable Heavy Metal Remediation. Volume 1: Principles and processes. Springer. Pp. 195-228. https://doi.org/10.1007/978-3-319-58622-9

Salvi, K. P., da Silva Oliveira, W., Horta, P. A., Rörig, L. R. & de Oliveira Bastos, E. (2021). A new model of Algal Turf Scrubber for bioremediation and biomass production using seaweed aquaculture principles. Journal of Applied Phycology 33, 2577-2586. https://doi.org/10.1007/s10811-021-02430-2

Sardans, J., Janssens, I. A., Ciais, P., Obersteiner, M. & Peñuelas, J. (2021). Recent advances and future research in ecological stoichiometry. Perspectives in Plant Ecology, Evolution and Systematics 50, 125611. https://doi.org/10.1016/j.ppees.2021.125611

Sayre, R. (2010). Microalgae: The potential for carbon capture. Bioscience 60 (9), 722–27. https://doi.org/10.1525/bio.2010.60.9.9

Scarcelli, P. G., Ruas, G., Lopez-Serna, R., Leite Serejo, M., Blanco, S., Arpád Boncz, M. & Munõz, R. (2021). Integration of algae-based´ sewage treatment with anaerobic digestion of the bacterial-algal biomass and biogas upgrading. Bioresource Technology 340, 125552. https://doi.org/10.1016/j.biortech.2021.125552

Schipper, K., Al-Jabri, H. M. S. J., Wijffels, R. H. & Barbosa, M. J. (2021) Techno-economics of algae production in the Arabian Peninsula. Bioresource Technology 331, 125043. https://doi.org/10.1016/j.biortech.2021.125043

Senhorinho, G. N. A., Laamanen, C. A. & Scott, J. A. (2019). New opportunities for closed mining sites: Bioprospecting for antibacterial agents. CIM Journal 10(2). DOI: 10.15834/CIMJ.2019.6 https://www.semanticscholar.org/paper/New-opportunities-for-closed-mining-sites%3A-for-Senhorinho-Laamanen/9e954d117f761d89ae2cbe0bf2c9e7c1c63c2ff9#citing-papers

Shanab, S., Essa, A. & Shalaby, E. (2012). Bioremoval capacity of three heavy metals by some microalgae species (Egyptian isolates). Plant Signalling & Behaviour 7(3), 392–9. https://doi.org/10.4161/psb.19173

Sharmila, V. G., Kumar, M. D., Pugazhendi, A., Bajhaiya, A. K., Gugulothu, P. & Banu, J. R. (2021). Biofuel production from macroalgae: present scenario and future scope. Bioengineered 12(2), 9216-9238. https://doi.org/10.1080/21655979.2021.1996019

Shayesteh, H., Vadiveloo, A., Bahri, P. A. & Moheimani, N. R. (2021). Can CO_2 addition improve the tertiary treatment of anaerobically digested abattoir effluent (ADAE) by *Scenedesmus* sp. (Chlorophyta)? Algal Research 58, 102379. https://doi.org/10.1016/j.algal.2021.102379

Shaygan, M., Mulligan, D., & Baumgartl, T. (2018). The potential of three halophytes (*Tecticornia pergranulata*, *Sclerolaena longicuspis*, and *Frankenia serpyllifolia*) for the rehabilitation of brine-affected soils. Land Degradation & Development 29(6), 2002-2014. https://doi.org/10.1002/ldr.2954

Shcherbatyuk, N., Wortman, S. E., McFadden, D., Weiss, B., Weyers, S., Ahmad, W., Bajwa, D. S., Galinato, S. P., Formiga, A., Gramig, G. & DeVetter, L. W. (2024). Alternative and emerging mulch technologies for organic and sustainable agriculture in the United States: A review. Hortscience 59(10), 1524-1533. https://doi.org/10.21273/HORTSCI18029-24

Shen, Y., Li, H., Zhu, W., Ho, S.-H., Yuan, W., Chen, J. & Xie, Y. (2017). Microalgal-biochar immobilized complex: A novel efficient biosorbent for cadmium removal from aqueous solution. Bioresource Technology 244, 1031–1038. https://doi.org/10.1016/j.biortech.2017.08.085

Sheoran, A. & Bhandari, S. (2005). Treatment of mine water by a microbial mat: bench-scale experiments. Mine Water and the Environment 24, 38–42. https://doi.org/10.1007/s10230-005-0069-z

Shivarkar, A. (2024). Microalgae Fertilizers Market Size to Hit USD 32.25 Bn by 2033. Precedence Research. May 9, 2024. https://www.precedenceresearch.com/microalgae-fertilizers-market

Siemon, D., Becker, F., Eckardt, L. & Robra-Bissantaz, S. (2019). One for all and all for one – towards a framework for collaboration support systems. Education Information Technology 24, 1837–1861. https://doi.org/10.1007/s10639-017-9651-9

Silva, R., Amancio, I. F. N., Andrade, A. R., Marinho Dos Santos, V. H., Santiago, P. S., Oliveira Granero, F., Malaguti Figueiredo, C. C. & Pereira Silva, L. (2022). Phytotoxic, cytogenotoxic, and insecticidal activities of compounds from extracts of freshwater *Lyngbya* sp. Journal of Toxicology and Environmental Health, Part A 85(21), 881–895. https://doi.org/10.1080/15287394.2022.2102100

Silva, S. C., Ferreira, I., Dias, M. M. & Barreiro, M. F. (2020). Microalgae derived pigments: A 10-year bibliometric review and industry and market trend analysis. Molecules 25(15), 3406. https://doi.org/10.3390/molecules25153406

Singh, R. P., Yadav, P., Kumar, I., Kumar Solanki, M., Roychowdhury, R., Kumar, A. & Kumar Gupta, R. (2023). Advancement of abiotic stresses for microalgal lipid production and its bioprospecting into sustainable biofuels. Sustainability 15(18), 13678. https://doi.org/10.3390/su151813678.

Singh, S. P. & Singh, P. (2014). Effect of CO_2 concentration on algal growth: A review. Renewable and Sustainable Energy Reviews 38, 172-179. https://doi.org/10.1016/j.rser.2014.05.043

Sirohi, R., Kumar Pandey, A., Ranganathan, P., Singh, S., Udayan, A., Kumar Awasthi, M., Hoang, A. T., Chilakamarry, C. R., Kim, S. H. & Sim, S. J. (2022). Design and applications of photobioreactors- a review. Bioresource Technology 349, 126858. https://doi.org/10.1016/j.biortech.2022.126858

Siville, B. & Boeing, W. J. (2020). Optimization of algal turf scrubber (ATS) technology through targeted harvest rate. Bioresource Technology Reports 9, 100360. https://doi.org/10.1016/j.biteb.2019.100360

Skjånes, K., Rebours, C. & Lindblad, P. (2013). Potential for green microalgae to produce hydrogen, pharmaceuticals and other high value products in a combined process. Critical Reviews in Biotechnology 33(2), 172–215. https://doi.org/10.3109/07388551.2012.681625

Slade, R. & Bauen, A. (2013). Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. Biomass and Bioenergy 53, 29–38. https://doi.org/10.1016/j.biombioe.2012.12.019

Solé-Bundó, M., Passos, F., Romero-Güiza, M. S., Ferrer, I. & Astals, S. (2019). Co-digestion strategies to enhance microalgae anaerobic digestion: A review. Renewable and Sustainable Energy Reviews 112, 471-482. https://doi.org/10.1016/j.rser.2019.05.036

Solovchenko, A., Gorelova, O., Selyakh, I., Pogosyan, S., Baulina, O., Semenova, L., Chivkunova, O., Voronova, E., Konyukhov, I., Scherbakov, P. & Lobakova, E. (2015). A novel CO_2 -tolerant symbiotic *Desmodesmus* (Chlorophyceae, Desmodesmaceae): Acclimation to and performance at a high carbon dioxide level. Algal Research 11, 399–410. https://doi.org/10.1016/j.algal.2015.04.011

Solovchenko, A. E., Ismagulova, T. T., Lukyanov, A. A., Vasilieva, S. G., Konyukhov, I. V., Pogosyan, S. I., Lobakova, E. S. & Gorelova, O. A. (2019). Luxury phosphorus uptake in microalgae. Journal of Applied Phycology 31(5), 2755–2770. https://doi.org/10.1007/s10811-019-01831-8

Soru, S., Malavasi, V., Concas, A., Caboni, P. & Cao, G. (2019). A novel investigation of the growth and lipid production of the extremophile microalga *Coccomyxa melkonianii* scca 048 under the effect of different cultivation conditions: Experiments and modeling. Chemical Engineering Journal 377, 120589. https://doi.org/10.1016/j.cej.2018.12.049

Souza, M. F. de, Meers, E. & Mangini, S. 2024. The potential of microalgae for carbon capture and sequestration. EFB Bioeconomy Journal 4, 100067. https://doi.org/10.1016/j.bioeco.2024.100067

Standards Australia (2023). Australian Standard AS 5812:2023 Manufacturing and marketing of pet food - Cats and dogs. https://www.standards.org.au/standards-catalogue/standard-details?designation=as-5812-2023

Steinberg, C. E. W., Schäfer, H. & Beisker, W. (1998). Do acid-tolerant cyanobacteria exist? Acta Hydrochimica et Hydrobiologica 26(1), 13–19. https://doi.org/10.1002/(SICI)1521-401X(199801)26:1<13::AID-AHEH13>3.0.CO;2-V

Steinbruch, E., Drabik, D., Epstein, M., Ghosh, S., Prabhu, M. S., Gozin, M., Kribus, A. & Golberg, A. (2020). Hydrothermal processing of a green seaweed Ulva sp. for the production of monosaccharides, polyhydroxyalkanoates & hydrochar. Bioresource Technology 318, 124263. https://doi.org/10.1016/j.biortech.2020.124263

Steunou, A.-S., Bhaya, D., Bateson, M. M., Melendrez, M. C., Ward, D. M., Brecht, E., Peters, J. W., Kühl, M. & Grossman, A. R. (2006). *In situ* analysis of nitrogen fixation and metabolic switching in unicellular thermophilic cyanobacteria inhabiting hot spring microbial mats. Proceedings of the National Academy of Sciences 103(7), 2398–2403. https://doi.org/10.1073/pnas.0507513103

Stevens, A. E., McCarthy, B. C. & Vis, M. L. (2001). Metal content of *Klebsormidium*-dominated (Chlorophyta) algal mats from acid mine drainage waters in Southeastern Ohio. Journal of the Torrey Botanical Society 128(3), 226–233. https://doi.org/10.2307/3088714

Subashchandrabose, S. R., Ramakrishnan, B., Megharaj, M., Venkateswarlu, K. & Naidu, R. (2013). Mixotrophic cyanobacteria and microalgae as distinctive biological agents for organic pollutant degradation. Environment International 51, 59–72. https://doi.org/10.1016/j.envint.2012.10.007

Summerfield, T. C. & Sherman, L. A. (2008). Global transcriptional response of the alkali-tolerant cyanobacterium *Synechocystis* sp. strain pcc 6803 to a pH 10 environment. Applied and Environmental Microbiology 74(17), 5276–5284. https://doi.org/10.1128/AEM.00883-08

Sun, C., Chen, J., Tian, K., Peng, D., Liao, X. & Wu, X. (2019a). Geochemical characteristics and toxic elements in alumina refining wastes and leachates from management facilities. International Journal of Environmental Research and Public Health 16(7), 1297. https://doi.org/10.3390/ijerph16071297

Sun, J., Wang, Y. & Gao, D. (2019b). Preparation and performance test of a condensed dust inhibitor. Mining Research and Development 39(04), 111–115. https://doi.org/10.13827/j.cnki.kyyk.2019.04.024

Sunda, W. G., Price, N. M. & Morel, F. M. (2005). Trace metal ion buffers and their use in culture studies. Algal Culturing Techniques 4, 35–63. DOI:10.1016/b978-012088426-1/50005-6

Suosaari, E. P., Reid, R. P., Araujo, T. A. A., Playford, P. E., Holley, D. K., McNamara, K. J. & Eberli, G. P. (2016). Environmental pressures influencing living stromatolites in Hamelin Pool, Shark Bay, Western Australia. Palaios 31(10), 483–496. https://www.jstor.org/stable/26780054

Susanti, H., Rahman, D. Y., Praharyawan, S. & Susilaningsih D. (2021). Characterization and identification of tropical lipid-producing microalgae isolated from abandoned kaolin and tin mine site in Belitung Island, Indonesia. Journal of Hunan University (Natural Sciences) 48(10), 571-576. http://jonuns.com/index.php/journal/article/view/824/819

Sutherland, D. L. & Craggs, R. J. (2017). Utilising periphytic algae as nutrient removal systems for the treatment of diffuse nutrient pollution in waterways. Algal Research 25, 496–506. https://doi.org/10.1016/j.algal.2017.05.023

Sutherland, D. L., Howard-Williams, C., Turnbull, M. H., Broady, P. A. & Craggs, R. J. (2015). Frequency of CO_2 supply affects wastewater microalgal photosynthesis, productivity and nutrient removal efficiency in mesocosms: implications for full-scale high rate algal ponds. Journal of Applied Phycology 27(5), 1901–1911. https://doi.org/10.1007/s10811-014-0437-9

Sydney, E. B., Schafranski, K., Barretti, B. R. V., Sydney, A. C. N., Zimmerman, J. F. D., Cerri, M. L. & Demiate, I. M. (2019). Biomolecules from extremophile microalgae: From genetics to bioprocessing of a new candidate for large-scale production. Process Biochemistry 87, 37–44. https://doi.org/10.1016/j.procbio.2019.09.012

Tan, K. M., Kassim, M. A., Ng, Z. J. & Lalung J. (2020). Isolation and characterization of novel acidophilic microalgae from abandoned mining site area for carbohydrate biosynthesis and its kinetic growth study in photobioreactor. IOP Conference Series: Materials Science and Engineering 716, 012011. https://doi.org/10.1088/1757-899X/716/1/012011

Tan, L. C., Nancharaiah, Y. V., van Hullebusch, E. D. & Lens, P. N. L. (2016). Selenium: environmental significance, pollution, and biological treatment technologies. Biotechnology Advances 34, 886–907. doi.org/10.1016/j.biotechadv.2016.05.005

Tank, M., Thiel, V., Ward, D. M. & Bryant, D. A. (2017). A Panoply of Phototrophs: An Overview of the Thermophilic Chlorophototrophs of the Microbial Mats of Alkaline Siliceous Hot Springs in Yellowstone National Park, WY, USA. In: Hallenbeck, P. (ed.) Modern Topics in the Phototrophic Prokaryotes. Springer, Cham. Pp. 87–137. https://doi.org/10.1007/978-3-319-46261-5_3

Tassé, N., Germain, M. D. & Bergeron, M. (1994). Composition of interstitial gases in wood chips deposited on reactive mine tailings - consequences for their use as an oxygen barrier. In: Alpers, C. N. & Blowes, D. W. (Eds.), Environmental Geochemistry of Sulfide Oxidation. American Chemical Society, Washington. Pp. 631-644. https://doi.org/10.1021/BK-1994-0550.CH038

Teng, F. Z., McDonough, W. F., Rudnick, R. L., Dalpé, C., Tomascak, P. B., Chappell, B. W. & Gao, S. (2004). Lithium isotopic composition and concentration of the upper continental crust. Geochimica et Cosmochimica Acta 68(20), 4167–4178. https://doi.org/10.1016/j.gca.2004.03.031

The International Network for Acid Prevention (INAP) (2009). Global Acid Rock Drainage Guide (GARD Guide). http://www.gardguide.com

Touloupakis, E., Cicchi, B., Benavides, A. M. S. & Torzillo, G. (2016). Effect of high pH on growth of *Synechocystis* sp. pcc 6803 cultures and their contamination by golden algae (*Poterioochromonas* sp.). Applied Microbiology and Biotechnology 100(3), 1333–1341. https://doi.org/10.1007/s00253-015-7024-0

Tripathi, S. & Poluri, K. M. (2021). Adaptive and Tolerance Mechanism of Microalgae in Removal of Cadmium from Wastewater. In: Mandotra, S. K., Upadhyay, A. K. & Ahluwalia, A. S. (Eds) Algae. Springer, Singapore. Pp. 63–88. https://doi.org/10.1007/978-981-15-7518-1_4

Unger, C., Lechner, A., Glenn, V., Edraki, M. & Mulligan, D. (2012). Mapping and prioritising rehabilitation of abandoned mines in Australia. In Proceedings of the Life of Mine Conference (AusIMM), Brisbane, Australia, 10–12 July 2012; pp. 259–266. https://onemine.org/documents/mapping-and-prioritising-rehabilitation-of-abandoned-mines-in-australia

Urrutia, C., Yañez-Mansilla, E. & Jeison, D. (2019). Bioremoval of heavy metals from metal mine tailings water using microalgae biomass. Algal Research 43, 101659. https://doi.org/10.1016/j.algal.2019.101659

Valente, T. & Gomes, C. L. (2007). The role of two acidophilic algae as ecological indicators of acid mine drainage sites. Journal of Iberian Geology 33(2), 283–294.

van Dam, R., Hogan, A., Harford, A. & Markich, S. (2008). Toxicity and metal speciation characterisation of waste water from an abandoned gold mine in tropical Northern Australia. Chemosphere 73(3), 305–313. https://doi.org/10.1016/j.chemosphere.2008.06.011

van der Meer, M. T., Klatt, C. G., Wood, J., Bryant, D. A., Bateson, M. M., Lammerts, L., Schouten, S., Damste, J. S., Madigan, M. T. & Ward, D. M. (2010). Cultivation and genomic, nutritional, and lipid biomarker characterization of *Roseiflexus* strains closely related to predominant in situ populations inhabiting yellowstone hot spring microbial mats. Journal of Bacteriology 192(12), 3033–42. https://doi.org/10.1128/jb.01610-09

Van Hille, R. P., Boshoff, G. A., Rose, P. D. & Duncan, J. R. (1999). A continuous process for the biological treatment of heavy metal contaminated acid mine water. Resources, Conservation and Recycling 27(1), 157-167. https://doi.org/10.1016/S0921-3449(99)00010-5

van Houten, R. T. & Lettinga, G. (1995). Treatment of acid mine drainage with sulphate-reducing bacteria using synthesis gas as energy and carbon source. Mededelingen Landbouwkundige en Toegepaste Biologische Wetenschappen, Gent University, Gent (Belgium) 60 (4 b), 2693–2700.

Van Langenhove, L., Verryckt, L. T., Bréchet, L., Courtois, E. A., Stahl, C., Hofhansl, F., Bauters, M., Sardans, J., Boeckx, P., Fransen, E., Peñuelas, J. & Janssens, I. A. (2020). Atmospheric deposition of elements and its relevance for nutrient budgets of tropical forests. Biogeochemistry 149(2), 175–193. https://doi.org/10.1007/s10533-020-00673-8

Vázquez-Romero, B., Antonio Perales, J., Pereira, H., Barbosa, M. & Ruiz, J. (2022) Techno-economic assessment of microalgae production, harvesting and drying for food, feed, cosmetics, and agriculture. Science of The Total Environment 837, 155742. https://doi.org/10.1016/j.scitotenv.2022.155742.

Verb, R. G. & Vis, M. L. (2000). Comparison of benthic diatom assemblages from streams draining abandoned and reclaimed coal mines and nonimpacted sites. Journal of the North American Benthological Society 19(2), 274–288. https://doi.org/10.2307/1468070

Verb, R. G. & Vis, M. L. (2001) Macroalgal communities from an acid mine drainage impacted watershed. Aquatic Botany 71(2), 93-107. https://doi.org/10.1016/S0304-3770(01)00184-X

Verified Market Report (2024). Global Chlorophyllin Market By Type (Sodium Copper Chlorophyllin, Other), By Application (Food Additive, Alternative Medicine), By Geographic Scope And Forecast. https://www.verifiedmarketreports.com/product/chlorophyllin-market-size-and-forecast/

Wang, H. T., Cheng, S., Wang, H., He, J., Fan, L. & Danilov, A. S. (2023). Synthesis and properties of coal dust suppressant based on microalgae oil extraction. Fuel 338, 127273. https://doi.org/10.1016/j.fuel.2022.127273

Wang, J., Liu, W., Chen, J., Wang, H., Liu, S. & Chen, S. (2016). Biotemplated mno/c microtubes from spirogyra with improved electrochemical performance for lithium-ion batteries. Electrochimica Acta 188, 210–217. https://doi.org/10.1016/j.electacta.2015.11.128

Wang, S., Mukhambet, Y., Esakkimuthu, S. & Abomohra, A. E.-F. (2022a). Integrated microalgal biorefinery – Routes, energy, economic and environmental perspectives. Journal of Cleaner Production 348, 131245. https://doi.org/10.1016/j.jclepro.2022.131245

Wang, H., Nche-Fambo, F. A., Yu, Z. & Chen, F. (2018). Using microalgal communities for high CO_2-tolerant strain selection. Algal Research 35, 253–261. https://doi.org/10.1016/j.algal.2018.08.038

Wang, H. K., Nie, W., Zhang, H. H., Jin, H., Bao, Q., Yan, J. Y. & Liu, Q. (2020). A synthesis of a dust suppressant using the cellulose extracted from maize straw. Starch-Starke 72(3-4), 1900187. https://doi.org/10.1002/star.201900187

Wang, X., Wang, L., Qi, Y. & Chen, J. (2022b). Sustainable Stabilization/Solidification of Mine Wastes. In: Tsang, D. C. W. & Wang, L. (Eds.) Low Carbon Stabilization and Solidification of Hazardous Wastes, Elsevier. Pp. 227-242. https://doi.org/10.1016/B978-0-12-824004-5.00009-8

Werner, T. T., Bach, P. M., Yellishetty, M., Amirpoorsaeed, F., Walsh, S., Miller, A., Roach, M., Schnapp, A., Solly, P., Tan, Y., Lewis, C., Hudson, E., Heberling, K., Richards, T., Chia, H. C., Truong, M., Gupta, T. & Wu, X. (2020). A geospatial database for effective mine rehabilitation in Australia. Minerals 10(9), 745. doi.org/10.3390/min10090745.

Worden, S., Svobodova, K., Côte, C. & Bolz, P. (2024). Regional post-mining land use assessment: An interdisciplinary and multi-stakeholder approach. Resources Policy 89, 104680. https://doi.org/10.1016/j.resourpol.2024.104680

World Bank Group (2024). Agricultural land (% of land area) – Australia. https://data.worldbank.org/indicator/AG.LND.AGRI.ZS?locations=AU

Wright, I. A., Paciuszkiewicz, K. & Belmer, N. (2018). Increased water pollution after closure of Australia’s longest operating underground coal mine: a 13-month study of mine drainage, water chemistry and river ecology. Water, Air & Soil Pollution 229(3), 55. doi.org/10.1007/s11270-018-3718-0

Yan, S., Cheng, K. Y., Ginige, M., P., Morris, C., Deng, X., Li, J., Song, S., Zheng, G., Zhou, L. & Kaksonen, A. H. (2022) Sequential removal of selenate, nitrate and sulfate and recovery of elemental selenium in a multi-stage bioreactor process with redox potential feedback control. Journal of Hazardous Materials 424(Part C), 127539. doi.org/10.1016/j.jhazmat.2021.127539.

Yan, S., Cheng, K. Y., Ginige, M. P., Zheng, G., Zhou, L. & Kaksonen, A. H. (2021). Optimization of nitrate and selenate reduction in an ethanol-fed fluidized bed reactor via redox potential feedback control. Journal of Hazardous Materials 402, 123770. https://doi.org/10.1016/j.jhazmat.2020.123770

Yang, Y., Zhao, J., Song, M., Yu, J., Yu, X., Ding, B. & Chen, X. (2023). Analysis of photosynthetic pigments pathway produced by CO_2-toxicity induced *Scenedesmus obliquus*. Science of The Total Environment 867, 161309. https://doi.org/10.1016/j.scitotenv.2022.161309

Yap, X. Y., Gew, L. T., Khalid, M. & Yow, Y. Y. (2023). Algae-based bioplastic for packaging: A decade of development and challenges (2010-2020). Journal of Polymers and the Environment 31(3), 833-851. https://doi.org/10.1007/s10924-022-02620-0

Yarnold, J., Karan, H., Oey, M. & Hankamer, B. (2019). Microalgal aquafeeds as part of a circular economy. Trends in Plant Science 24(10), 959-970. https://doi.org/10.1016/j.tplants.2019.06.005

Yates, K. K. & Robbins, L. L. (1998). Production of carbonate sediments by a unicellular green alga. American Mineralogist 83(11), 1503–1509. https://doi.org/10.2138/am-1998-11-1238

Young, R. E., Gann, G. D., Walder, B., Liu, J. G., Cui, W. H., Newton, V., Nelson, C. R., Tashe, N., Jasper, D., Silveira, F. A. O., Carrick, P. J., Hagglund, T., Carlsén, S. & Dixon, K. (2022). International principles and standards for the ecological restoration and recovery of mine sites. Restoration Ecology 30 (supplement 2), e13771. https://doi.org/10.1111/rec.13771

Young, P., Taylor, M. J., Buchanan, N., Lewis, J. & Fallowfield, H. J. (2019). Case study on the effect continuous CO_2 enrichment, via biogas scrubbing, has on biomass production and wastewater treatment in a high rate algal pond. Journal of Environmental Management 251, 109614. https://doi.org/10.1016/j.jenvman.2019.109614

Yuan, H., Ge, T., Chen, C., O'Donnell, A. G. & Wu, J. (2012). Significant role for microbial autotrophy in the sequestration of soil carbon. Applied and Environmental Microbiology 78(7), 2328–2336. https://doi.org/10.1128/AEM.06881-11

Yun, H.-S., Lee, H., Park, Y.-T., Ji, M.-K., Kabra, A. N., Jeon, C., Jeon, B.-H. & Choi, J. (2014). Isolation of novel microalgae from acid mine drainage and its potential application for biodiesel production. Applied Biochemistry and Biotechnology 173(8), 2054–2064. https://doi.org/10.1007/s12010-014-1002-3

Yun, J.-H., Smith, V. H. & Pate, R. C. (2015). Managing nutrients and system operations for biofuel production from freshwater macroalgae. Algal Research 11, 13–21. https://doi.org/10.1016/j.algal.2015.05.016

Xu, L. X., Brilman, D. W. F., Withag, J. A. M., Brem, G. & Kersten, S. (2011). Assessment of a dry and a wet route for the production of biofuels from microalgae: Energy balance analysis. Bioresource Technology 102(8), 5113-5122. https://doi.org/10.1016/j.biortech.2011.01.066

Xu, K., Du, M., Yao, R., Luo, J., Chen, Z., Li, C., Lei, A. & Wang, J. (2024). Microalgae-mediated heavy metal removal in wastewater treatment: Mechanisms, influencing factors, and novel techniques. Algal Research 82, 103645. https://doi.org/10.1016/j.algal.2024.103645

Xu, S. Y., Huang, X. & Cheong, K. L. (2017). Recent advances in marine algae polysaccharides: Isolation, structure, and activities. Marine Drugs 15(12). https://doi.org/10.3390/md15120388

Zhang, X., An, L., Tian, J., Ji, B., Lu, J. & Liu, Y. (2023b). Microalgal capture of carbon dioxide: A carbon sink or source? Bioresource Technology 390, 129824. https://doi.org/10.1016/j.biortech.2023.129824

Zhang, J., Zhang, J., Deng, Y., Wu, C., Li, H., Qing, Z., Li, J. & Zhang, W. (2023a), Quantitative evaluation of ecological and environmental impacts caused by future mining. Ore Geology Reviews 162, 105672. https://doi.org/10.1016/j.oregeorev.2023.105672.

Zhou, G., Zhang, X. Y., Li, S. L., Wang, Q., Xu, Y. X. & Song, R. X. (2023). New type of sawdust-based dust suppressant during tunnelling and underground space: Preparation, characterization and engineering application. Construction and Building Materials 365, 12. https://doi.org/10.1016/j.conbuildmat.2022.130085

Zhu, S., Wang, Y., Shang, C., Wang, Z., Xu, J. & Yuan, Z. (2015). Characterization of lipid and fatty acids composition of *Chlorella zofingiensis* in response to nitrogen starvation. Journal of Bioscience and Bioengineering 120(2), 205–209. 10.1016/j.jbiosc.2014.12.018

Zou, Y., Zeng, Q., Li, H., Liu, H. & Lu, Q. (2021). Emerging technologies of algae-based wastewater remediation for bio-fertilizer production: a promising pathway to sustainable agriculture. Journal of Chemical Technology and Biotechnology 96(3), 551–563. https://doi.org/10.1002/jctb.6602

Appendix A

Engaged stakeholders

Alcoa

BHP

ChemCentre

Department of Biodiversity, Conservation and Attractions, Western Australia

Department of Environment, Parks and Water Security, Northern Territory

Department of Water and Environmental Regulation, Western Australia

Energy Australia

Environment Protection Authority, Tasmania

Evolution Mining

Fortescue

Heidelberg Materials

Mine Land Rehabilitation Authority, Victoria

MRIWA

Pershke Consulting Pty Ltd

Queensland Mine Rehabilitation Commissioner

Regional Economic Solutions Pty Ltd

Rio Tinto

South 32

In addition to the above stakeholders, 13 other government agencies, mining or consultancy companies and universities were contacted without response.