



REPORT NO. M10615

**Investigating the Valorisation Potential of Tailings for
Mineral Carbonation**

Results of research carried out as MRIWA Project [M10615]

at The University of Western Australia

by

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Project Context and Scope

This report was produced as part of a Cooperative Education for Enterprise Development (CEED) Industry Placement project undertaken by the named author while enrolled as a student at The University of Western Australia, with support from the Minerals Research Institute of Western Australia (MRIWA). The work comprised a structured review of relevant literature, publicly available datasets, and pilot-scale studies within the defined scope of the placement.

The work constitutes a desktop-based scoping study intended to inform early-stage understanding of the potential for mineral carbonation through mine-waste valorisation in Western Australia. The analysis relies on existing databases and published sources and uses geological and spatial properties as proxy measures for tailings characteristics. No site-specific sampling, geochemical or mineralogical characterisation, experimental testing, or techno-economic assessment was undertaken as part of this project.

Accordingly, the findings, site screening, and rankings presented are indicative only and should not be interpreted as assessments of technical feasibility, economic viability, regulatory suitability, or commercial readiness. The conceptual framework developed is intended to support future research prioritisation and data collection. Further detailed characterisation, validation, and feasibility analysis would be required before any decisions regarding pilot-scale or commercial implementation could be considered.

Executive Summary

The valorisation of mine tailings through mineral carbonation offers a dual benefit of mitigating environmental risks associated with Tailings Storage Facilities (TSFs) while contributing to large-scale carbon dioxide removal (CDR). Western Australia hosts some of the world's largest TSFs, many of which are derived from ultramafic and mafic lithologies that are rich in magnesium- and calcium-bearing silicates. These minerals, including serpentine, olivine, and pyroxenes, can react with CO₂ to form stable carbonates, enabling permanent geological storage. The primary objective of this study was to assess the existing databases related to mine tailings in Western Australia, particularly focusing on their suitability for assessing the tailings as a possible feedstock for mineral carbonation, and to identify and recommend the specific types of information that such a database should contain to aid site screening and prioritisation. A comparative evaluation of the Atlas of Australian Re-mining Potential and the MINEDEX database identified MINEDEX as the most comprehensive source of available mine site data/information. Geological datasets from the Geological Survey of Western Australia (GSWA) were integrated into a GIS framework to identify the mine sites operating within ultramafic and mafic zones. The research further developed a conceptual framework based on a review of pilot projects, evaluating various factors such as mineralogy and particle size on the carbonation efficiency. Analysis indicated that tailings from ultramafic-hosted nickel deposits and kimberlite-hosted diamond mines possess high magnesium silicate contents, enabling significant theoretical CO₂ sequestration potential, in contrast to low-reactivity gold and iron ore tailings. The findings suggest that large, mineralogically suitable TSFs could serve as strategic hubs for industrial-scale mineral carbonation in Western Australia.

Table of Contents

Project Context and Scope	2
Executive Summary	3
Terms, Abbreviations and Acronyms	5
List of Figures	5
List of Tables.....	5
1. Introduction	6
1.1. Minerals research/industry challenge and background	6
1.2. Objectives of the research.....	9
2. Methodology	10
2.1. Methodology for Database Analysis	10
2.2. Methodology for Conceptual Framework Development	11
3. Results and Findings	12
3.1. Database Analysis and Site Identification	12
3.1.1. Global tailings Portal	12
3.1.2. Atlas of Australian Re-mining Potential.	13
3.1.3. MINEDEX	14
3.1.4. POLYGON.....	15
3.1.5. Geospatial Analysis of WA Tailings Storage Facilities	17
3.2. Pilot-Scale Evidence for Framework Development	20
3.2.1. MCI Project.....	20
3.2.2. CARMEX Project.....	21
3.2.3. Québec Process.....	22
4. Discussion	23
4.1. Interpretation of the Distribution and Suitability of TSFs in WA	23
4.2. Pilot-Scale Insights for Framework Design.....	25
4.3. Framework Structure and Evaluation Criteria.....	26
5. Conclusions	27
6. Recommendations for further work.....	28
6.1. Enhancing Existing Tailings Database	28
6.2. Addressing Knowledge Gaps in Carbonation Potential of Tailings	29
7. References	30

Terms, Abbreviations and Acronyms

CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CMMI	Critical Minerals Mapping Initiative
CO ₂	Carbon Dioxide
MRIWA	Minerals Research Institute of Western Australia
PSD	Particle Size Distribution
TSF	Tailings Storage Facility
WA	Western Australia
WRL	Waste Rock Landform

List of Figures

Figure 1 - Application of mineral carbonation of mining waste for mine waste management and rehabilitation (adapted from Azadi et al., 2019).	7
Figure 2 - Location of the TSFs identified in Australia in Global tailings Portal.....	13
Figure 3 - The ultramafic and mafic formations (in blue) of WA extracted from the merged geological map.....	17
Figure 4 - Centroids of open pit mines (from POLYGON dataset) operating within ultramafic and mafic geological units in WA.	18
Figure 5 - Centroids of TSFs associated with mines operating within ultramafic and mafic geological units.	19
Figure 6 - Carbonation yield (%) as a factor of time (in hrs) for the MCI and CARMEX projects. (Modified from Benhelal et al., 2018, Bodénan et al., 2014)	21
Figure 7 - Scatter plot of SiO ₂ % versus (CaO+MgO+FeO) % contents of different mine tailings (adapted from Norouzpour et al., 2025).....	23
Figure 8 - Ten largest nickel and diamond TSFs by surface area.	24
Figure 9 - Top 10 nickel and diamond TSFs in Western Australia ranked by surface area (POLYGON dataset).	25

List of Tables

Table 1- : Proposed conceptual framework for assessing mine-waste suitability for mineral carbonation.	26
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1. Introduction

The mining sector in Western Australia (WA) generates vast volumes of mine waste, which represent ongoing environmental and economic liabilities for society. Such liabilities might be significantly reduced if mine waste materials could be valorised, thereby encouraging their recycling. One potential use of mine waste is for carbon dioxide (CO₂) sequestration by mineral carbonation. In addition, achieving the Paris Agreement target of limiting warming to 1.5–2°C will require large-scale carbon dioxide removal (CDR) strategies capable of capturing up to 10 gigatonnes of CO₂ annually by 2050 (Bullock et al., 2021). While conventional carbon capture and storage (CCS) methods have progressed, challenges such as long-term leakage risks, monitoring costs, and site-specific geological constraints limit their deployment (Snæbjörnsdóttir et al., 2020). In this context, mineral carbonation has emerged as a safe and permanent alternative, offering the potential to bind CO₂ into geologically stable minerals (Saran et al., 2018). However, any assessment of opportunities to valorise mine wastes requires knowledge of their physical and compositional properties, and databases documenting Western Australian mine wastes (e.g., MINEDEX (Department of Mines, Petroleum and Exploration [DMPE], 2025); Atlas of Australian Re-mining Potential (Geoscience Australia, 2021); Global Tailings Portal (Frank et al., 2021) provide limited information in relation to material characteristics.

This project investigates the potential to use mine waste in WA as feedstock for accelerated mineral carbonation. It evaluates the current level of knowledge of geochemical and mineralogical properties of different tailings materials stored in tailings storage facilities (TSFs) that might be used for mineral carbonation, identifies gaps in that knowledge, develops a conceptual framework for assessing the mineral carbonation potential of such facilities, and makes recommendations for future research.

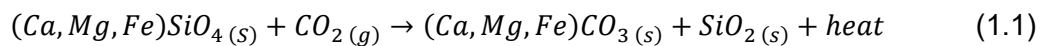
1.1. Minerals research/industry challenge and background

Mining is a major sector of the WA economy, and the increasing waste stream it generates poses significant environmental and economic challenges. Mine waste is conventionally managed through containment strategies such as tailings dams and stockpiles, which require ongoing monitoring and rehabilitation, contributing to long-term liabilities. Current practices focus primarily on containment and risk mitigation rather than on resource recovery or reuse, resulting in underutilised material with latent potential (Araujo et al., 2022; Carneiro & Fourie, 2019; Kinnunen et al., 2022).

The Western Australian Government, via its Minerals Research Institute of Western Australia (MRIWA), recognises the potential of mineral carbonation and is actively seeking to accelerate its development (MRIWA, 2024). Initiatives such as the Accelerated Mineral Carbonation Research Program aim to catalyse advancements in this field, focusing on converting CO₂ into stable forms using mining waste and byproducts.

Mineral carbonation refers to the geochemical process by which CO₂ is permanently sequestered by reacting with silicate minerals, particularly ultramafic minerals, and converting them into thermodynamically stable carbonate minerals such as calcite (CaCO₃), magnesite (MgCO₃), and siderite (FeCO₃) (Seifritz, 1990).

This process emulates the natural silicate weathering that occurs over geological timescales but can be accelerated via engineered systems to offer a secure, leakage-free, and long-term route for CCS pathway. The general chemical reaction is given below.



This reaction is exothermic in the forward direction, and thermodynamically favourable under ambient conditions, particularly for minerals with high Gibbs free energy differences between the reactants and products (Li et al., 2018, Marín et al., 2021). The carbonation process typically occurs in two main stages: (i) dissolution of the mineral matrix and (ii) precipitation of carbonate minerals. However, the kinetics of silicate dissolution in water are slow under natural conditions, limiting spontaneous carbonation rates.

Figure 1, taken from Azadi et al. (2019), illustrates the schematic model of an integrated mineral carbonation route, and it also demonstrates that the carbonated products derived from mineral carbonation of mine tailings can be repurposed for mine reclamation and acid mine drainage (AMD) management, thereby adding value to the materials otherwise considered as waste. Therefore, this project proposes that using mine tailings as feedstock for mineral carbonation not only offers a solution for permanently locking the CO₂ but also provides economic and environmental benefits in managing mine waste.

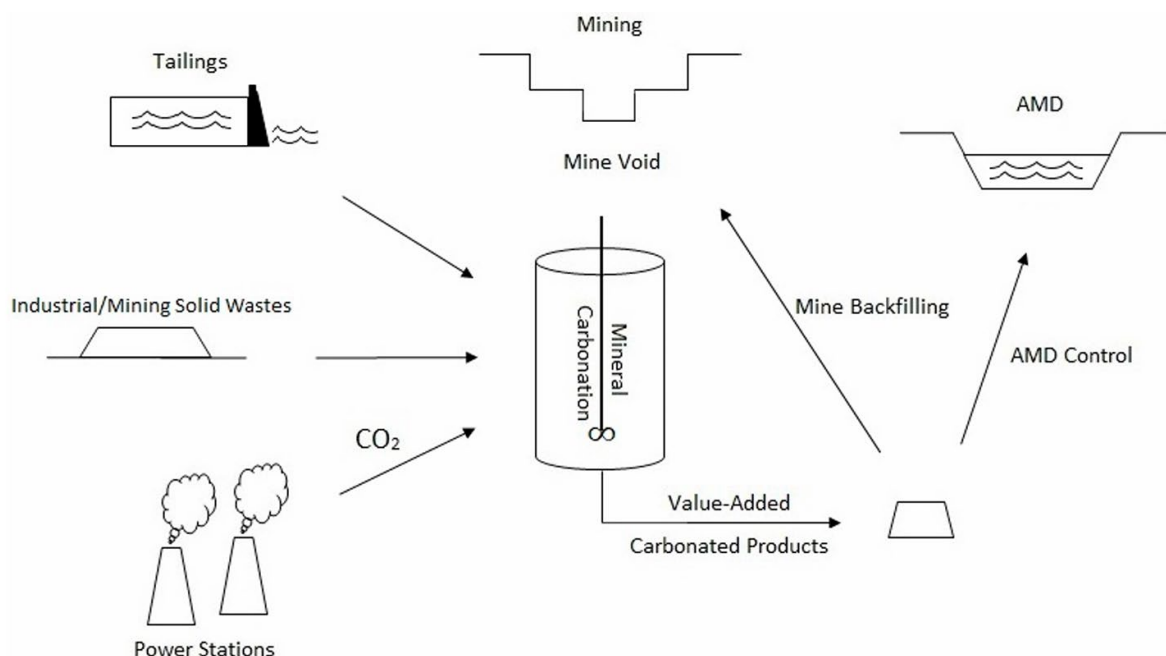


Figure 1 - Application of mineral carbonation of mining waste for mine waste management and rehabilitation (adapted from Azadi et al., 2019).

Mining generates vast quantities of tailings, often accounting for 60–99% of ore mined (Bullock et al., 2021). These wastes are typically ground to fine particle sizes (10–1,000 μm), providing high reactive surface areas favourable for carbonation (Li et al., 2018). Tailings from ultramafic and mafic deposits, such as those from nickel, diamond, asbestos, and certain platinum group metal mines, present promising opportunities due to their enrichment in reactive Mg- and Ca-bearing minerals like olivine, serpentine, and brucite (Norouzpour et al., 2025). Globally, mine tailings have the potential to capture between 1.1–4.5 Gt CO_2 annually, although only 3–21% of this capacity may be realised within 50 years under current dissolution rates (Bullock et al., 2021).

Ultramafic mine tailings can carbonate passively when exposed to the atmosphere and water within tailings storage facilities, forming hydrated Mg-carbonates (e.g., nesquehonite, hydromagnesite) that persist over long periods; in some sites, this has offset on the order of one-tenth of annual CO_2 emissions without active intervention. However, passive rates are highly variable and controlled by CO_2 supply, mineral dissolution kinetics, tailings handling (subaerial vs subaqueous), and local climate (Li et al., 2018). At Mount Keith (WA), for example, passive carbonation is CO_2 -supply-limited; at Diavik, subaqueous storage restricts CO_2 ingress and carbonic acid generation, further slowing dissolution (Stokreef et al., 2022). Identifying the rate-limiting step (CO_2 supply vs dissolution vs precipitation) is therefore essential before any attempt to “optimize” passive pathways. Accelerated carbonation refers to the engineered processes that deliberately manipulate operational variables (PSD, temperature, pCO_2 , slurry concentration, solution chemistry, residence time) and/or apply activation (mechanical, chemical, thermal) to overcome the dissolution and improve overall conversion.

WA hosts extensive ultramafic and mafic rock formations, producing significant volumes of mine tailings. For this study, the expected tailings mineralogy is inferred from the underlying geology rather than from site specific tailings analyses, with Mt Keith the documented exception where brucite in tailings has been confirmed. On that geological basis the tailings are expected to be rich in serpentine and olivine with minor brucite. Although brucite can carbonate quickly, its reaction is often CO_2 -limited even under CO_2 -rich settings, so outcomes depend on enhancing CO_2 delivery and/or activation. These characteristics make WA tailings strong candidates for accelerated approaches that target the identified bottlenecks (Norouzpour et al., 2025; Li et al., 2018). In addition, using mine tailings as feedstock for mineral carbonation offers several potential benefits. It contributes to CO_2 reduction targets and promotes sustainable mining practices by repurposing waste materials. The process has the potential to mobilise critical minerals such as nickel that are often present in tailings, providing both environmental and economic advantages for the mining sector.

1.2. Objectives of the research

This research aims to evaluate the potential for valorising Western Australia’s mine waste through mineral carbonation by addressing key knowledge gaps and data limitations. The primary objectives of the study are to:

- i. Analyse existing mine-waste databases, including POLYGON, MINEDEX, the Atlas of Australian Re-mining Potential, and the Global Tailings Portal, to assess their suitability for identifying tailings amenable to mineral carbonation.
- ii. Identify tailings storage facilities in Western Australia that exhibit favourable geological and mineralogical characteristics for carbon dioxide removal (CDR).
- iii. Develop a conceptual framework that enables systematic assessment of mine-waste carbonation potential, based on mineralogical reactivity, physical properties, and operational feasibility.
- iv. Provide recommendations to improve future mine-waste data collection to better support carbon-utilisation opportunities in the State.

1.3. Scope

The scope of this project is limited to a desktop-based investigation involving the analysis of publicly accessible mine-waste databases and relevant literature. The study focuses on tailings generated from mining operations in Western Australia and does not include experimental testing or new mineralogical data acquisition. The research evaluates database completeness, identifies suitable sites for accelerated mineral carbonation, and synthesises existing scientific findings to design a conceptual assessment framework. The outcomes of the project are intended to inform MRIWA’s ongoing development of a mine-waste database and support future decision-making for potential pilot-scale mineral carbonation initiatives in WA.

2. Methodology

This research project employed a desktop-based approach integrating literature review, database analysis, and geospatial mapping to evaluate the valorisation potential of mine waste in WA for mineral carbonation. The methodology was structured around two core objectives: (1) analysing existing databases to identify tailings suitable for mineral carbonation, and (2) developing a conceptual framework for assessing mine-waste suitability based on global pilot studies.

2.1. Methodology for Database Analysis

The first objective of this research was to analyse existing mine-waste databases to identify suitable tailings deposits in WA for mineral carbonation. This objective was achieved through a structured desktop-based methodology integrating database interrogation, attribute filtering, spatial analysis, and cross-referencing with geological and commodity information. The approach was designed to assess the comprehensiveness, completeness and relevance of existing data for evaluating mine-waste suitability and to visualise spatial trends that could inform future sampling and site prioritisation.

This study focused on identifying and analysing mine sites in WA located within ultramafic and mafic rock units, as these are considered to be the most prospective for producing tailings suitable for mineral carbonation. The process began with a comparative assessment of three key datasets: MINEDEX (DMPE, 2025); Atlas of Australian Re-mining Potential (Geoscience Australia, 2021); and the Global Tailings Portal (Frank et al., 2021). Although all the three datasets contain valuable spatial and commodity information, the MINEDEX dataset was found to identify a significantly greater number of mine sites across Western Australia. Given this broader coverage and higher resolution of site-level data, MINEDEX was initially selected as the primary source for this study. However, to overcome the limitations of the MINEDEX database, particularly the absence of mapped site footprints, the yet-to-be-published Mining Residue Polygon (hereafter referred to as POLYGON) database was used for the subsequent spatial analysis and mapping.

To support the spatial analysis, GIS-based geological base maps of Western Australia were obtained from the Geological Survey of Western Australia's (GSWA) publicly accessible GeoVIEW.WA database. Three datasets were used: (i) the 1:100,000 scale Bedrock Geology of WA, (ii) the 1:500,000 scale Bedrock Geology of WA, and (iii) the 1:500,000 scale Bedrock Geology of WA – Cenozoic. These datasets provide detailed lithological classifications and have been widely used in mineral prospectivity studies (Aitken et al., 2018; Duuring & Laukamp, 2016). This methodological framework intends to establish a replicable, transparent approach for screening tailings repositories as potential mineral-carbonation feedstocks and lays the groundwork for integrating geochemical data in future updates.

2.2. Methodology for Conceptual Framework Development

The second objective of this research aimed to develop a conceptual framework for evaluating the suitability of mine waste for mineral carbonation. While the initial stage focused on identifying potential tailings sites through geospatial and database analysis, this phase sought to translate existing knowledge from international pilot projects and scientific studies into a structured, decision-support framework applicable to WA.

This phase employed an extended literature-review methodology, and the process drew upon peer-reviewed journal articles from leading mineral carbonation initiatives worldwide. An extensive search across major scientific databases such as Web of Science, and Google Scholar, identified 3 major mineral carbonation projects deployed in pilot scale. A comparative analysis was conducted between these projects to benchmark best practices and extract design principles.

3. Results and Findings

The results are presented under this section in two parts. The first part outlines findings from database interrogation and geospatial analysis, highlighting spatial patterns, data gaps, and high-potential tailings sites whereas the second part synthesises insights from global pilot projects and literature to construct a framework for assessment.

3.1. Database Analysis and Site Identification

The analysis of the MINEDEX (DMPE, 2025); Atlas of Australian Re-mining Potential (Geoscience Australia, 2021); and the Global Tailings Portal (Frank et al., 2021) datasets yielded an integrated overview of mine-waste sites across WA relevant to mineral carbonation. The findings affirm that WA possesses a significant inventory of TSFs.

3.1.1. Global tailings Portal

The Global Tailings Portal is a voluntary disclosure-driven registry that compiles the information reported by companies on their TSFs in response to the request made by the Investor Mining and Tailings Safety Initiative in 2019 following major dam failures (GRID-Arendal, 2020). As reported by Franks et al. (2021), the Global Tailings Portal is a dataset that records coordinates, construction and raising method, height, stored volume, consequence hazard categories, and stability review history for 1,743 facilities globally. It provides unprecedented visibility into engineering and risk attributes, but it does not include either the geochemistry or mineralogy of the tailings.

For Western Australia, only 180 tailings storage facilities were reported in the Global Tailings Portal (as shown in Figure 2), which is low given the scale of mining in the state and from the known number of tailings storage facilities in WA. This likely reflects the scope of the portal, which focuses on publicly listed companies, and its emphasis on the stability of TSFs and governance rather than materials characterization. In addition, the reporting was voluntary, so all companies might not have submitted their data or disclosed their facilities. As a result, although Global Tailings Portal fields such as location, dam type and raising method, height, volume, and hazard or risk are useful for context and cross checking, they cannot by themselves identify sites suitable for mineral carbonation. However, the height and volume fields may be indicting potential volume or mass of the material available to processing.



Figure 2 - Location of the TSFs identified in Australia in Global tailings Portal.

3.1.2. Atlas of Australian Re-mining Potential.

The Atlas of Australian Re-mining Potential is a national geospatial database of tailings storage facilities developed through the integration of multiple national and state-level datasets with visual interpretation of satellite imagery in Google Earth Pro (Sarker et al., 2022). The geographic coordinates of hard-rock mine sites were first sourced from the Mining Incidence Documentation and Assessment Scheme (MIDAS) (Werner et al., 2020) and systematically imported into Google Earth Pro for detailed visual inspection. The identified TSFs were then documented with their name, point based coordinates, state, operational status, waste type, storage type, backfill and rehabilitation flags, and, where available, height and volume. The data were exported in Keyhole Markup Language (KML) format, processed in Microsoft Excel, and spatially analysed in ArcMap 10.6 to produce shapefiles and state-wise distribution maps. Datasets like MINEDEX (WA) and the Global Tailings Portal were also incorporated and validated to ensure consistency and completeness (Sarker et al., 2022). It

also links each waste feature to its associated mines/deposits, deposit commodities, and deposit models that follow the Critical Minerals Mapping Initiative (CMMI) classification scheme, enabling queries by deposit style for re-mining assessments (Hofstra et al., 2021). Sarker et al. (2022) states that the methodology used to develop the database has effectively minimized false detections from morphologically similar landscape features and established a reproducible framework for future geospatial and environmental analyses relevant to mine waste valorisation and resource recovery. The Atlas can therefore be used to identify TSFs with potential for mineral carbonation where facilities are associated with deposit types commonly hosted by ultramafic rocks, for example nickel deposits, applying the same geology led screening logic used with MINEDEX and POLYGON. However, the Atlas database is not as comprehensive as MINEDEX or POLYGON in WA, so it is best used as a complementary source rather than a primary dataset for TSF inventory and prioritisation.

For this project, the dataset was filtered to extract the mine waste entries corresponding to Western Australia, which yielded a total of 654 records. By recorded waste type, the distribution comprises 369 tailings, 176 wastes from mineral excavations, 6 fly-ash units, 43 leach residues, 52 general mine-waste sites, 4 magnetic-separation tailings, 2 milling-waste sites, 1 cobbing-waste site, and 1 slag site. However, the database does not include mineralogical, geochemical, or particle-size data and for this reason it could not be used as a stand-alone source to identify TSFs suitable for accelerated mineral carbonation in this study.

3.1.3. MINEDEX

MINEDEX is the WA Government's statewide register of mines and mineral deposits that provides a coordinated, point based, project-based inquiry system for site identification and context, forming the foundation for resource mapping and mine data integration across the state. The key site-level attributes recorded in the dataset includes information on site locations (coordinates), type, reported mineral resources and production, inspection data, and links to environmental reports, which together enable consistent discovery and cross-referencing of WA mining assets.

In this study, the MINEDEX database was downloaded as a shapefile and analysed using QGIS software. It was found that the dataset has a total of 47,395 entries, of which 23,658 were classified as Mines and 2,852 as Infrastructure. In addition, the database identifies 949 TSFs for WA of which 828 categorised under Infrastructure and 121 under Mines. These figures indicate that MINEDEX captures a large share of WA TSFs relative to other available databases. However, the study done by Sarker et al. (2022) reported duplicate site points at identical coordinates and some records plotted offshore, highlighting issues with geolocation precision and deduplication. Since the validation of the data points were out of scope of this project the entries were not visually checked against satellite imagery. However, it is worth noting that the number of tailings storage facilities identified in MINEDEX in this study (approximately 1,000) is consistent with the count reported by Sarker et al. (2022). None of these sites are located offshore, suggesting that the offshore coordinates mentioned by Sarker et al. (2022) may have resulted from data-extraction or filtering differences. Their observation that many sites lacked visible signs of TSFs likely reflects the inclusion of records classified as "proposed" within MINEDEX (i.e., where SITE_STAGE = 'proposed' and the facility has not yet been constructed). This distinction highlights the importance of understanding dataset

structure and attribute definitions when interpreting spatial outputs from MINEDEX and other WA mining datasets.

When filtered specifically for TSF records, MINEDEX identifies nearly 1,000 sites, a figure comparable to the national compilation by Sarker et al., although some discrepancies persist. This difference likely arises because MINEDEX includes “proposed” facilities (records where SITE_STAGE = ‘proposed’), which represent planned but unconstructed sites. Many of these do not show visible surface features, as they may be rehabilitated, reprocessed, or still awaiting approval. In contrast, the Mining Residue Polygon Database identifies over 1,700 existing facilities, confirming that MINEDEX is not yet fully comprehensive.

While MINEDEX provides valuable geospatial and operational context, including information on commodities, mineralisation style, and production, it lacks the tailings-specific parameters required to assess mineral carbonation potential. Critical data such as mineralogical and geochemical composition (e.g., MgO, CaO, FeO content), dominant mineral phases (olivine, serpentine, pyroxene), particle-size distribution, and tailings tonnage or density are absent. Likewise, there is no detailed information on TSF design, material handling methods, or storage conditions, all of which influence carbonation efficiency and reactivity.

Despite these limitations, MINEDEX remains a valuable starting point for identifying and classifying mine sites across Western Australia. Its extensive spatial coverage and geological context provide an overview of mining activity in the state. However, the database could not be used directly for spatial analysis in this study because it does not include the mapped footprints of mine sites or TSFs, only their point locations. As a result, the Mining Residue Polygon database was used for subsequent stages of the research, as it provides polygon-based representations of open pit mines and TSFs that are essential for assessing their spatial extent, estimating areal coverage, and integrating geological context for evaluating mineral carbonation potential. However, to enhance its relevance for carbon utilisation studies, future updates should incorporate chemical and mineralogical attributes of mine wastes and improve spatial precision and metadata consistency.

3.1.4. POLYGON

The Mining Residue Polygon Database, developed by GSWA, provides a polygon-based spatial inventory of mining residue features across Western Australia. Unlike MINEDEX, which records mine sites as point locations, this dataset captures the actual mapped footprints of the open pit mines, TSFs, and waste rock dumps. Each record represents a discrete polygon feature with attributes describing feature type, location and commodity.

In this study, the polygon dataset was used as the primary spatial layer for analysing the distribution and areal extent of TSFs across Western Australia. As of May 2025, the dataset contains 2,833 open pits and 4,986 mine waste features, of which 1,676 are TSFs and 3,049 are waste rock landforms (WRLs), offering significantly broader coverage than MINEDEX, which lists approximately 950 sites. The inclusion of polygon geometries enabled the calculation of surface area estimates and supported geospatial correlation with geological and lithological datasets, including the 1:100,000 and 1:500,000 scale bedrock geology maps from GSWA. The analysis showed that 1,572 mines occur within mafic and ultramafic rock units,

which are lithologies typically rich in Mg- and Ca-bearing silicates such as olivine, pyroxene, and serpentine, favourable for mineral carbonation. The project codes of these mines were then cross-referenced using QGIS to identify associated TSFs, resulting in a total of 1,055 TSFs. These findings demonstrate that a substantial proportion of WA's tailings are derived from rock types with high theoretical carbonation potential, providing a strong foundation for prioritising sites for further geochemical assessment and pilot-scale investigation.

The polygon database therefore provided the necessary spatial precision and completeness for this research, supporting accurate overlay analysis in QGIS and allowing visual inspection of tailings locations relative to surrounding geological units. However, while the dataset offers detailed geometric representation, it still lacks chemical, mineralogical, and physical property data for the stored materials. Consequently, the bedrock geology underlying each open pit mine site was used as a proxy indicator of mineralogical composition to infer carbonation potential.

Another important limitation of the POLYGON dataset is the absence of information describing material flows between mining operations and their associated TSFs. This gap is not unique to POLYGON but is also present in all the other databases reviewed in this report, including MINEDEX, the Atlas of Australian Re-mining Potential, and the Global Tailings Portal. Without these linkages, it is not possible to trace the origin of tailings or determine how different ore sources and processing streams contribute to each facility, which restricts any detailed assessment of tailings composition, variability, and potential suitability for mineral carbonation. In this study, open-pit mines located within mafic and ultramafic rock units were identified, and corresponding TSFs were filtered using matching project codes, under the assumption that each mine disposes of its waste material into the TSF with the same project code. However, this assumption introduces a degree of uncertainty. The datasets do not explicitly record waste transport routes or deposition linkages, making it unclear whether certain TSFs receive material from multiple mines or whether waste is redirected across projects during different operational phases.

This limitation reduces the reliability of attributing specific tailings compositions to individual mine lithologies and may result in misclassification of feedstock suitability for mineral carbonation. To address this issue, future version of the dataset should incorporate explicit material flow relationships, including source-to-sink mapping between mine sites and their corresponding TSFs. A well-documented material flow component would significantly enhance the interpretive value of the dataset by enabling tracing of ore processing streams and deposition pathways. Such information could assist in estimating the bulk mineralogical composition of tailings, even in the absence of direct geochemical data. It would also help distinguish single-source from multi-source TSFs, reducing uncertainty in evaluating their carbonation potential.

Overall, the Mining Residue Polygon Database served as a critical dataset for this study, providing the geospatial foundation for mapping, classification, and spatial correlation of TSFs across Western Australia. Its integration with geological and database-derived information enabled the identification of potential carbonation feedstocks and formed the basis for subsequent framework development and site prioritisation.

3.1.5. Geospatial Analysis of WA Tailings Storage Facilities

The 1:100,000 and 1:500,000 scale bedrock geology datasets were merged to produce a composite map that combined the high-resolution detail of the 1:100,000 dataset with the broader spatial coverage of the 1:500,000 dataset. Since the dataset contained numerous lithological codes that required expert interpretation, the merging steps and rock-code classifications were provided by GSWA, as their technical guidance ensured accurate representation of geological units. The mafic and ultramafic formations were then extracted from the merged geological layer (shown in Figure 3 below) and it was used as the foundation for filtering the mine sites.

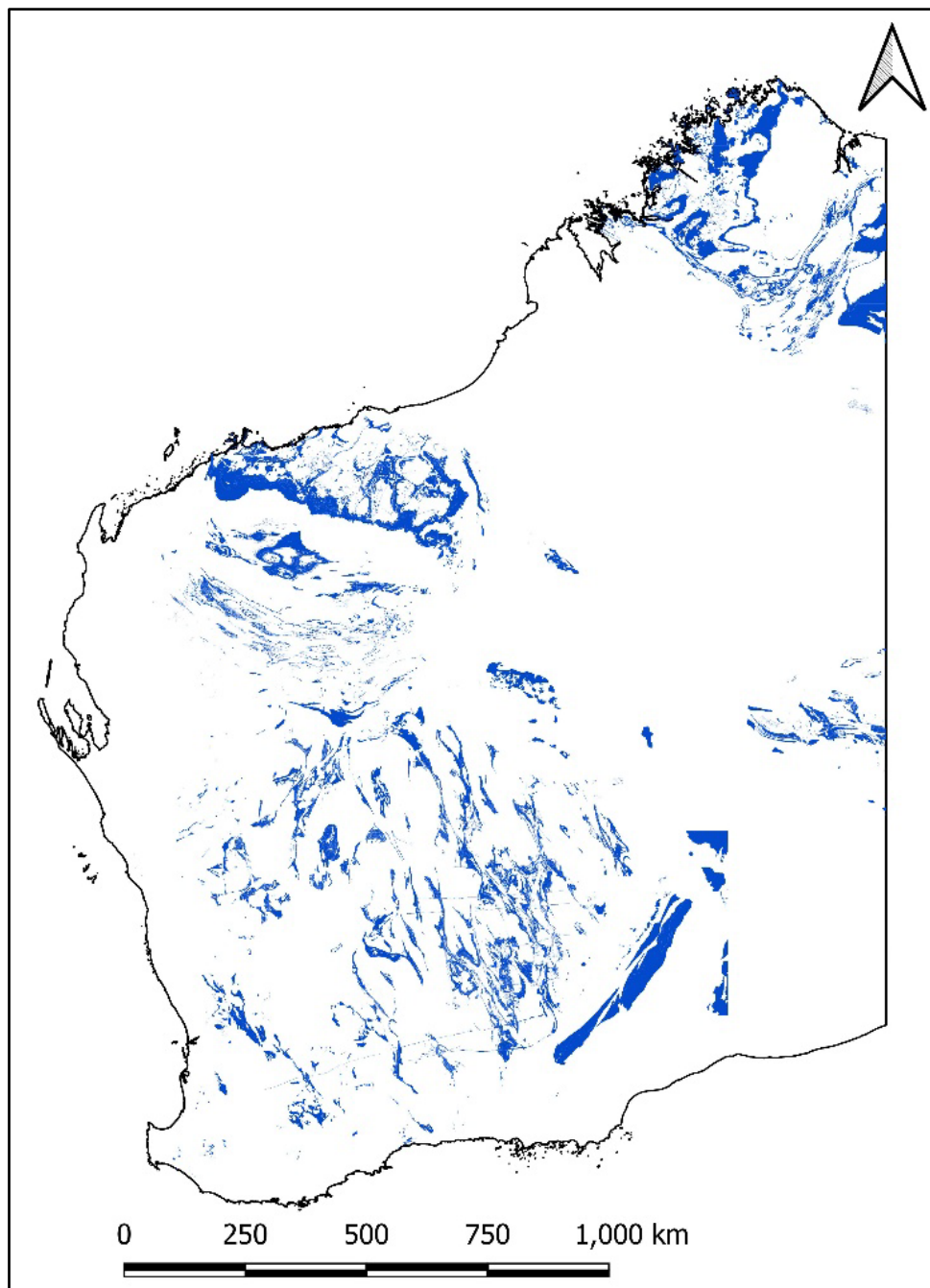


Figure 3 - The ultramafic and mafic formations (in blue) of WA extracted from the merged geological map.

The analysis began with the use of the MINEDEX database (DMPE, 2025), which provides spatial point data on active and historical mines. However, MINEDEX is limited in that it records only the geographic coordinates of mine feature “centroids”, without providing details of the footprint of the mining pit. A further limitation is that the recorded centroid is not guaranteed to fall within the actual feature, which can misrepresent location when intersecting with geology or performing spatial analysis. To overcome this limitation, GSWA provided access to its yet-to-be-published POLYGON database. This dataset records the spatial footprint of open pits and the TSFs, which can serve as a proxy for estimating the volume and mass of material extracted from or contained within these features. Using GIS-based spatial querying, mine sites identified in the POLYGON dataset was overlaid on the merged geological map, and the sites operating within ultramafic and mafic geological units were extracted (shown in Figure 4 below). These lithologies are particularly relevant for mineral carbonation due to their probable abundance of magnesium- and calcium-rich silicate minerals such as olivine, serpentine, and pyroxenes, which are highly reactive with CO₂.

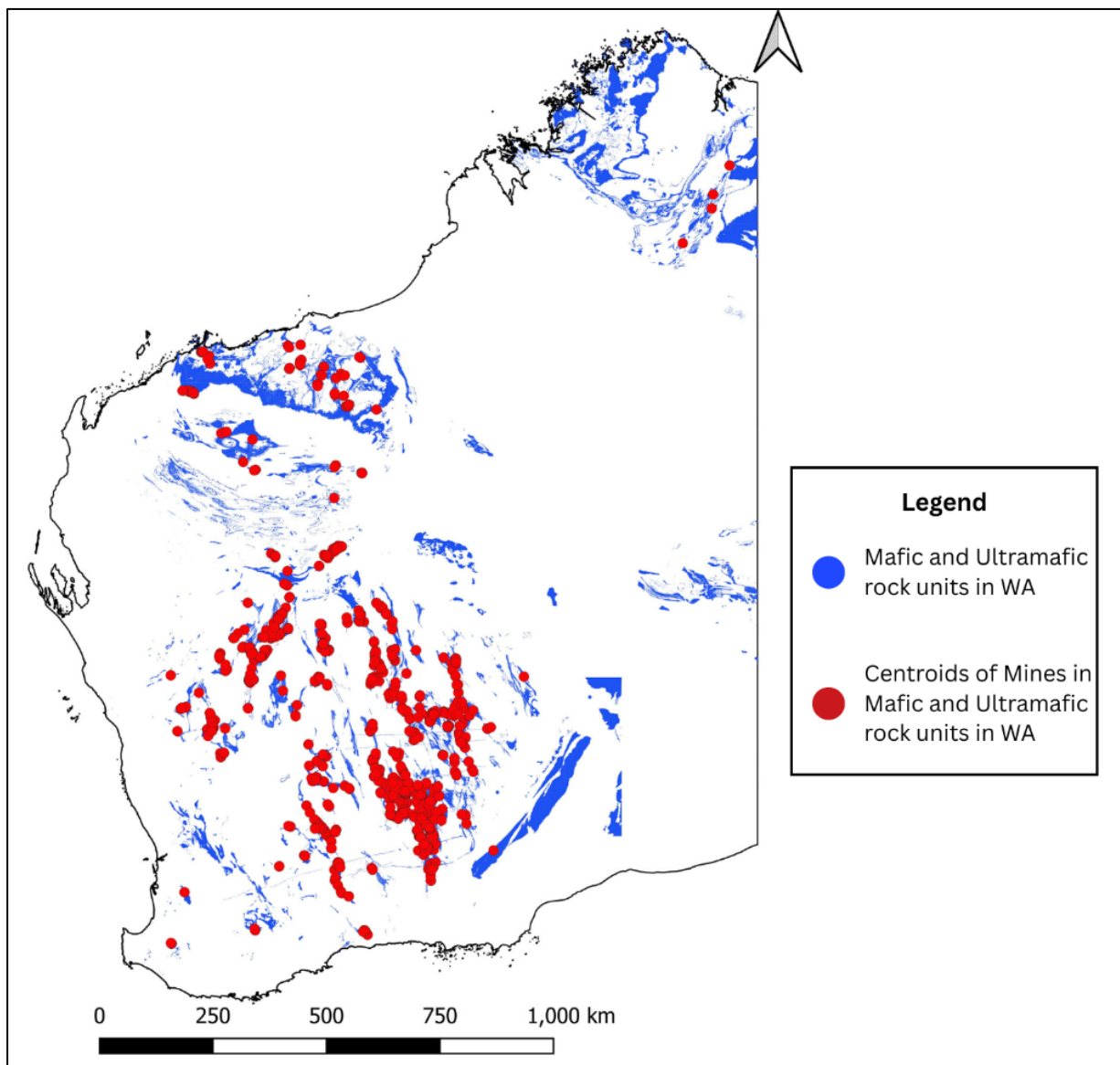


Figure 4 - Centroids of open pit mines (from POLYGON dataset) operating within ultramafic and mafic geological units in WA.

The filtering process generated a subset of open pits and associated TSFs (location shown in Figure 5 below) that were then ranked based on their surface area, which served as a proxy for their storage capacity given the absence of volume data in the POLYGON dataset.

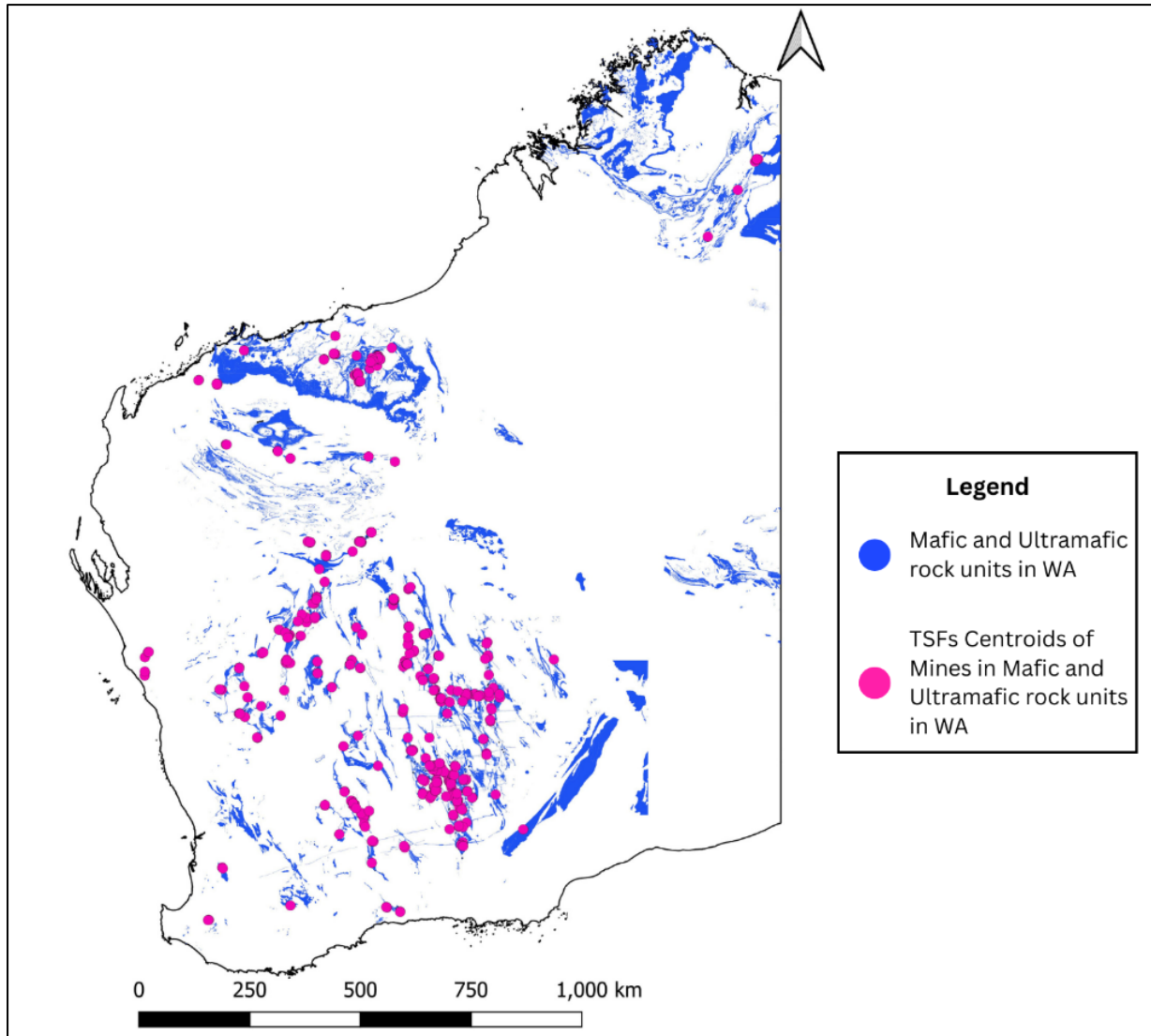


Figure 5 - Centroids of TSFs associated with mines operating within ultramafic and mafic geological units.

3.2. Pilot-Scale Evidence for Framework Development

The second objective of this project was to develop a conceptual framework for evaluating the suitability of tailings in WA for mineral carbonation. To support this, a review was conducted of three pilot-scale mineral-carbonation projects that tested tailings or ultramafic minerals as feedstock. These pilot studies provide practical performance data beyond laboratory conditions.

The three projects reviewed here includes heat-activated Mg-silicate feedstocks (MCi), a direct ex-situ route (CARMEX), and an indirect aqueous process scaled from lab to pilot (Québec Process). Reviewing these pilot projects is important because they demonstrate the practical efficiency of different carbonation routes, highlight the scale-up barriers that emerge when moving from controlled experiments to continuous operation, and provide real-world data on CO₂ uptake and conversion efficiencies. By comparing pilot outcomes across distinct technological approaches, this review helps identify the critical factors that can potentially determine whether MC using mine tailings as feedstock can become a viable carbon storage solution at industrial scale.

3.2.1. MCi Project

The MCi study uses a single-stage aqueous mineral carbonation of heat-activated lizardite at pilot scale and compares those data with laboratory results, with the aim of probing scale-up effects and repeatability (Benhelal et al., 2018). The study uses two feeds: an industrial kiln product (P.H.A) and a laboratory kiln product (L.H.A), and it emphasizes how feed characteristics and hydrodynamics affect magnesite yield (Benhelal et al., 2018).

In this pilot plant, the experiments were conducted in a custom 30 L batch reactor designed for up to 200 °C and 250 bar, typically operated at 150 °C, 150 bar CO₂, 15 wt % solids, and, when specified, 0.64 M NaHCO₃ (with comparative runs in deionized or tap water and with 1 M NaCl) (Benhelal et al., 2018). The vessel employs a hollow-shaft, gas-inducing impeller with six 45° pitched blades and four internal baffles to intensify gas–liquid–solid contact. The sampling was done using a pressurized pot and products were recovered through a filter press (Benhelal et al., 2018).

Under the standard window (150 °C; 150 bar CO₂; 15 wt % solids; 0.64 M NaHCO₃), magnesite yield rose rapidly to ≈20 wt % within 10 min and reached ~33 wt % at 5 h; end-point agreement between sampler (34 wt %) and discharge (33 wt %) confirmed repeatability (Benhelal et al., 2018). Relative to an otherwise similar 600 mL lab reactor, the pilot produced 35 ± 2 % higher yield, attributed to improved gas induction, baffling, and higher impeller tip speed that remove or prevent passivating precipitates on particle surfaces (Benhelal et al., 2018). Additive tests showed NaHCO₃ significantly increased yield (≈+30% vs. no additive), whereas 1 M NaCl had little effect; tap vs. deionized water gave essentially identical yields when NaHCO₃ was present (Benhelal et al., 2018). In complementary dissolution (first-stage) tests at 45 °C and 6.5 bar CO₂ with 2 wt % solids, Mg extraction reached ~50–54 wt % in 2 h for L.H.A./P.H.A. and showed similar trends in lab and pilot units (Benhelal et al., 2018). A common kinetic feature across runs is a rate decrease after ~10–60 min, consistent with

passivating-layer effects unless hydrodynamics continually refresh reactive surfaces (Benhelal et al., 2018).

3.2.2. CARMEX Project

The CARMEX project evaluates an ex-situ, direct aqueous mineral carbonation of ultramafic rocks and nickel slags, alongside a life-cycle assessment (LCA) of candidate flowsheets (Bodénan et al., 2014). Since the use of nickel slag for mineral carbonation and LCA analysis falls out of scope of this study, it has been excluded in this report. The baseline tests used 180°C, 10–20 bar CO₂, and solid loadings of 90 g L⁻¹, with particle sizes typically <100 µm for rocks. Additional runs were conducted to examine the effect of inorganic additives on the mineral carbonation efficiency (Bodénan et al., 2014).

The results highlight a strong dependence on both passivation control and process intensification. Under the baseline window (180 °C; 10–20 bar CO₂; 90 g L⁻¹; water only), rock conversions were low—typically ≤ 7 % in 24 h and, more generally, ~3–15 %—due to rapid formation of silica-rich passivation layers on reacting grains (Bodénan et al., 2014). In contrast, introducing continuous mechanical exfoliation (attrition/gas-dispersion impeller) at 180 °C and 20 bar CO₂ suppressed passivation and delivered ~70 % Mg conversion in ~4 h and > 90 % within < 24 h without heat activation of serpentine; adding 1 M NaCl + 0.64 M NaHCO₃ further accelerated early-time kinetics (Bodénan et al., 2014).

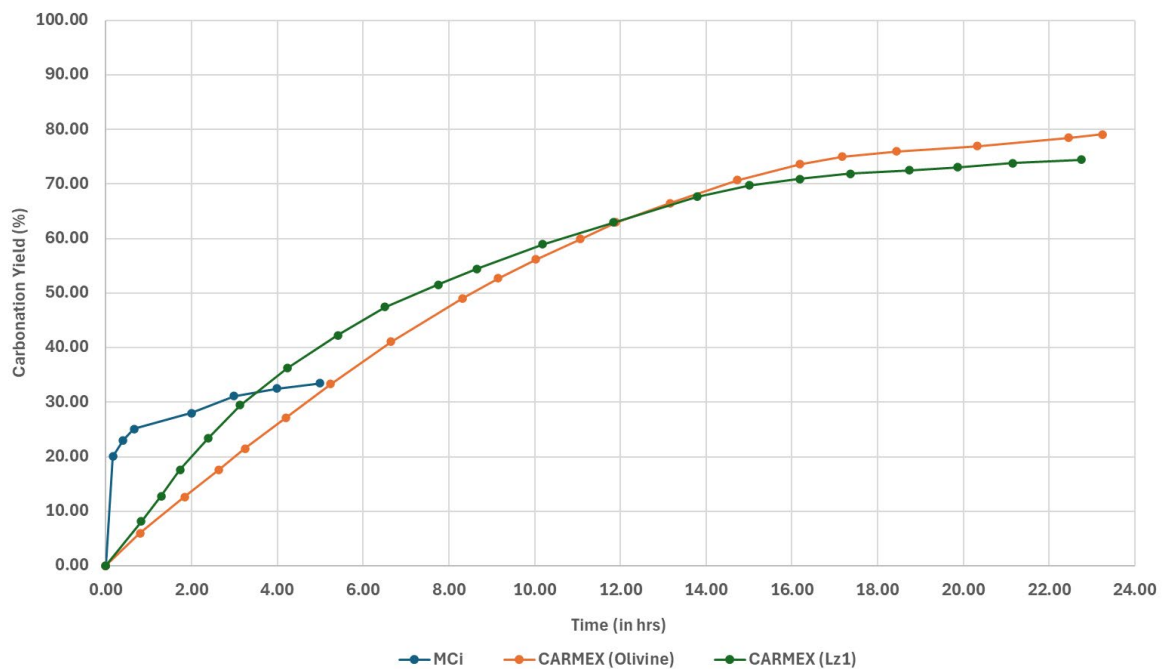


Figure 6 - Carbonation yield (%) as a factor of time (in hrs) for the MCI and CARMEX projects. (Modified from Benhelal et al., 2018, Bodénan et al., 2014).

3.2.3. Québec Process

The Québec pilot project tested indirect aqueous mineral carbonation using a pH swing route in which leaching and precipitation are run as distinct steps on serpentinite-based tailings using real cement-plant flue gas, moved from lab to pilot scale to probe performance under industrial conditions (Kemache et al., 2017). The unit was a Parr 18.7 L reactor operated in batch mode with 600 rpm agitation, solid–liquid ratio 150 g L⁻¹, gas–liquid ratio 3, and total pressure 2–10 atm. Each run comprised six gas batches of 15 min residence; the liquid was replaced after every two batches (≈30 min liquid residence) while the solids remained for ≈90 min. Two Mg-rich residues were tested: MCol and MJef. Both were magnetite-reduced, then crushed/ground to median sizes of ~67 μm (MCol) and ~47 μm (MJef) and heat-treated at 650°C for 30 min to enhance reactivity.

4. Discussion

This section interprets the key findings from the results and explains their significance in the context of evaluating mine-waste suitability for mineral carbonation in Western Australia (WA).

4.1. Interpretation of the Distribution and Suitability of TSFs in WA

Of the top 15 TSFs by area, nine were associated with gold mines, three with nickel, two with iron, and one with diamond. These deposits appear to represent suitable feedstocks for mineral carbonation, based solely on their host rock geology as they are derived from mines located within ultramafic and mafic terrains, which are typically enriched in Mg- and Ca-rich silicates. However, the compositional analysis published by Norouzpour et al. (2025) demonstrates that not all tailings derived from ultramafic and mafic rocks are suitable (as illustrated in Figure 7). According to their study, gold tailings cluster in the high-SiO₂ field, confirming very low reactivity, while iron ore tailings are dominated by FeO, with carbonation reactivity further constrained by oxidation. In contrast, nickel and diamond tailings consistently plot in the high-MgO field, which corresponds to the presence of abundant reactive silicates such as olivine, serpentine, and pyroxenes.

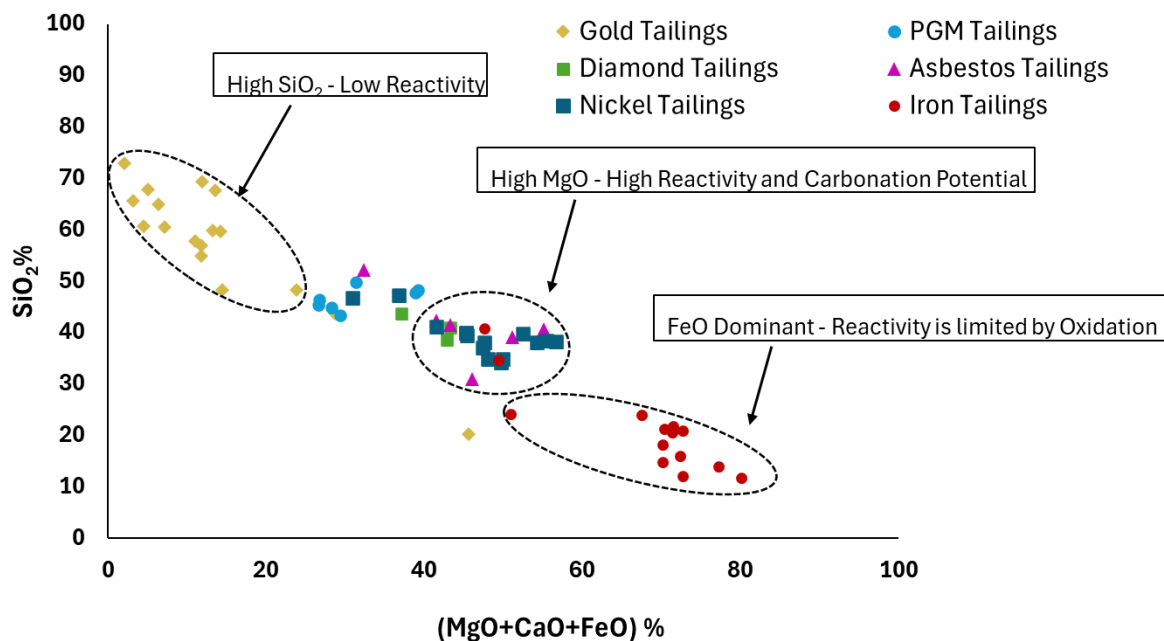


Figure 7 - Scatter plot of SiO₂% versus (CaO+MgO+FeO) % contents of different mine tailings (adapted from Norouzpour et al., 2025).

These results indicated that, despite their large collective volumes, gold and iron ore TSFs are less suitable as carbonation feedstock, whereas nickel and diamond TSFs offer both scale and favourable mineralogical signatures for mineral carbonation. Therefore, to further refine the analysis, the study then focused exclusively on TSFs of nickel and diamond mines and the ten largest nickel and diamond TSFs by surface area are shown in Figure 8.

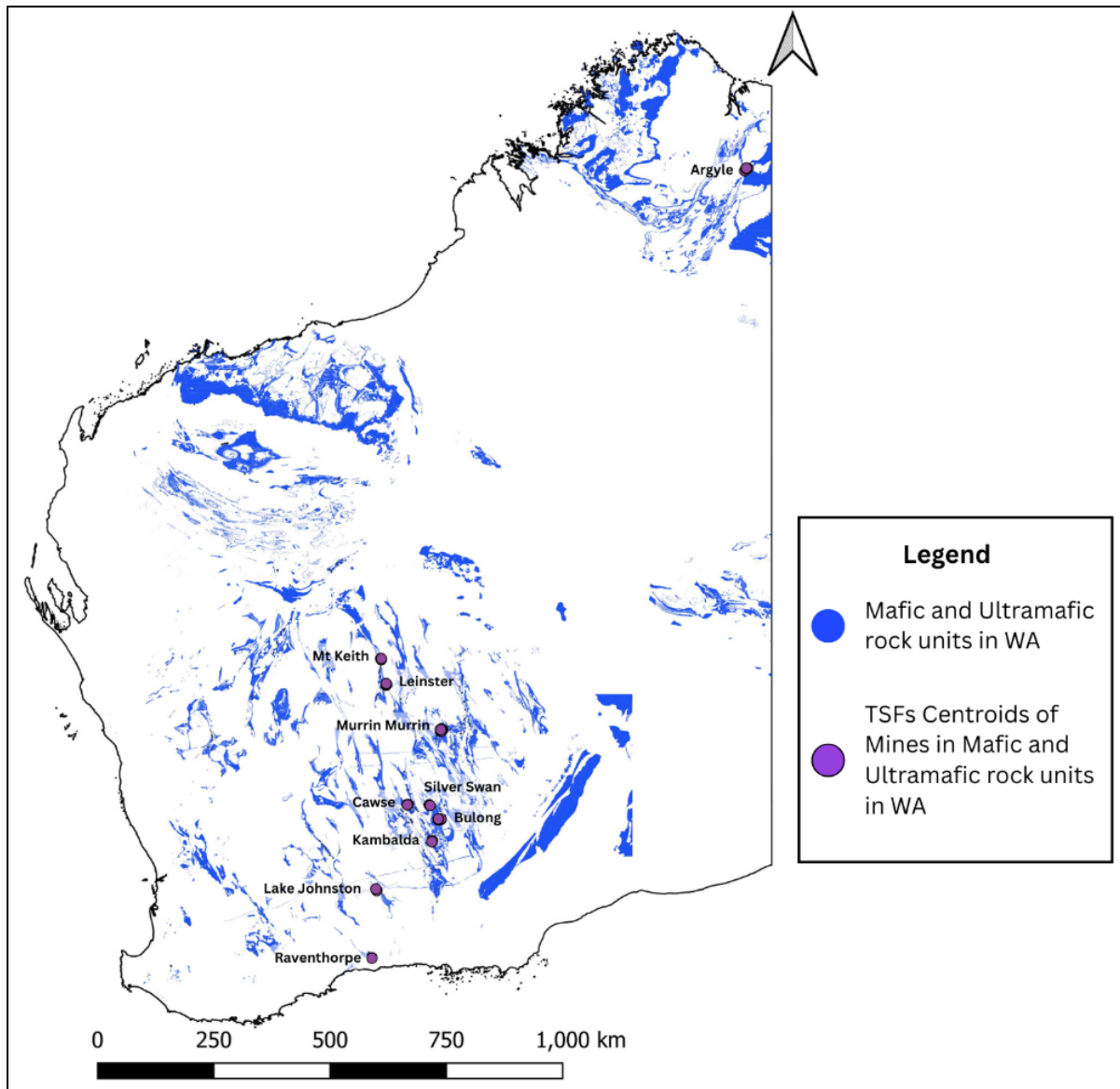


Figure 8 - Ten largest nickel and diamond TSFs by surface area.

The largest facility is the Mt Keith nickel operation, with a tailings footprint exceeding 15×10^6 m², followed by Murrin Murrin and the Argyle diamond mine, each with areas greater than 5×10^6 m². Other significant projects include Ravensthorpe, Leinster, Bulong, Cawse, Silver Swan–Black Swan, Lake Johnston, and Kambalda (illustrated in Figure 9 below).

Filtering the POLYGON dataset and integrating it with the bedrock maps provided by GSWA has revealed that Ni and diamond mines operate within mafic and ultramafic lithologies as expected. Generally, in a mine, the host rock of the ore is mined out and sent to the processing plant for extracting the ore metal and the remaining waste material is discharged from the plant and forms the tailings. The bulk composition of the bedrock was used as a proxy for mineral carbonation potential, because the detailed mineralogical data of the TSFs in Western Australia are currently unavailable. This approach assumes that the mineralogical composition of the underlying bedrock is a broad indicator of the primary lithologies that contribute to the tailings. Due to limited site-specific mineralogical data, a “typical” mineral assemblage for each rock type (e.g., mafic or ultramafic units) is inferred rather than directly measured. These

geological units host Mg and Ca rich silicates like olivine, pyroxenes and serpentine which are highly reactive for mineral carbonation. Based on this inferred mineralogy, the primary aim of the project to identify the suitable tailings deposits in Western Australia has been partly achieved because the inferred mineralogical data suggests that the Ni and diamond mine tailings may serve as a viable feedstock for mineral carbonation.

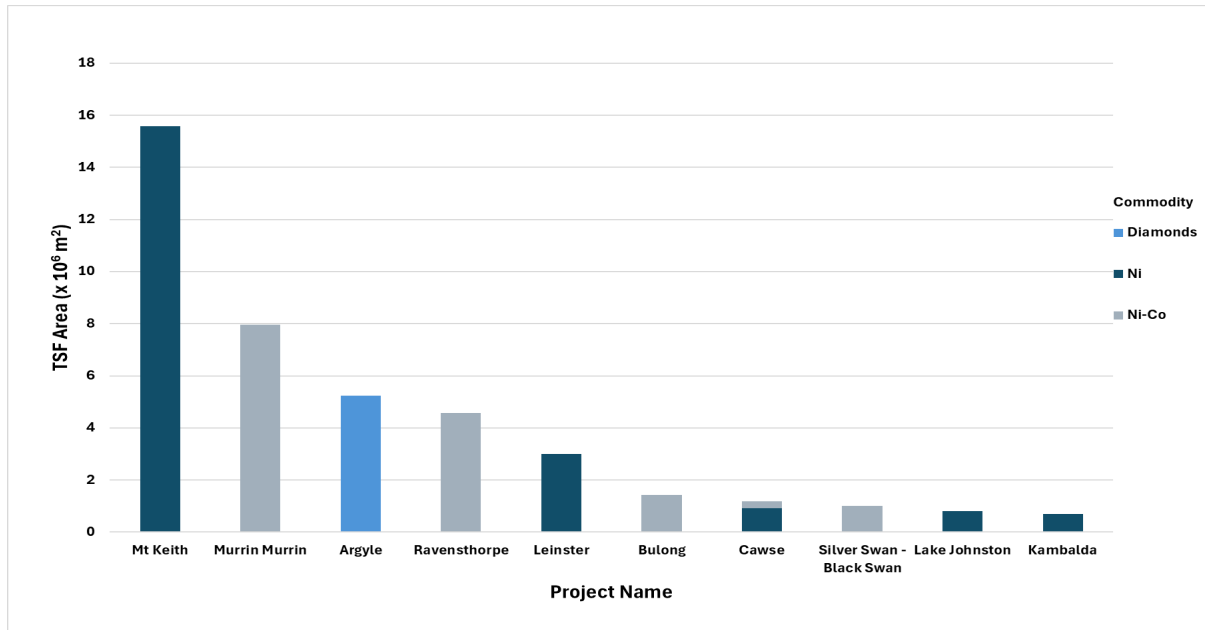


Figure 9 - Top 10 nickel and diamond TSFs in Western Australia ranked by surface area (POLYGON dataset).

TSFs may contain chemically altered, or heterogeneous materials that are not accurately represented by primary bedrock lithologies. As a result, relying solely on bedrock maps introduces a certain level of uncertainty into the carbonation potential assessment. It was challenging to account for site-specific variations because the absence of geochemical and mineralogical data from actual tailings limits the precision of these estimates. Furthermore, this approach does not capture the local differences in mineralogy, grain size distribution, and degree of weathering which can significantly influence the reactivity of mine waste toward CO₂, potentially affecting both the efficiency and feasibility of mineral carbonation processes (Gadikota et al., 2014; Harrison et al., 2013).

4.2. Pilot-Scale Insights for Framework Design

The review of pilot projects was conducted to evaluate scalability of mineral carbonation processes and to assess the influence of key operational variables on overall process efficiency. While laboratory studies provide valuable insight into mineral carbonation reaction kinetics, their findings are often constrained by small sample sizes, idealised conditions, and short timescales. Pilot-scale projects bridge this gap by testing mineral carbonation under semi-industrial settings where operational challenges such as feedstock variability, energy integration, slurry handling, and reactor design can be properly assessed.

4.3. Framework Structure and Evaluation Criteria

The conceptual framework developed in this project could provide a structured approach for evaluating the suitability of mine waste as feedstock for mineral carbonation in WA. It integrates both scientific parameters derived from mineralogical and geochemical principles and practical considerations informed by operational, and data-availability constraints. The guiding philosophy of the framework is to establish a transparent, data-driven, and scalable assessment model that can be progressively refined as more geochemical and process data become available. A basic structure of the framework is provided in Table 1 below, and the framework is organised into five interdependent assessment categories, each representing a critical dimension of carbonation feasibility.

Table 1- Proposed conceptual framework for assessing mine-waste suitability for mineral carbonation.

Item	Evaluation Category	Indicative Parameters	Relevance
1	Mineralogical Suitability	%MgO, %CaO, dominant silicate phases (serpentine, olivine, etc.).	Determines intrinsic carbonation potential of the tailings.
2	Physical Characteristics	Particle size, surface area, tailings tonnage (or volume).	Influences kinetics of carbonation and practical scalability.
3	Operational Characteristics	Current status of the TSF (operating or shut).	
4	Process and Infrastructure Feasibility	Proximity to CO ₂ source, energy demand, process type (direct carbonation or indirect carbonation).	Evaluates technical and logistical integration with existing facilities.
5	Data Completeness and Confidence	Availability of geochemical, mineralogical and spatial data.	Indicates reliability for decision-making.

5. Conclusions

This research investigated the potential for valorising mine waste in Western Australia (WA) through mineral carbonation, focusing on two key objectives: analysing existing mine-waste databases to identify suitable tailings, and developing a conceptual framework for assessing their carbonation potential. Through the integration of the Polygon dataset and the bedrock geology maps of Western Australia, a comprehensive geospatial overview of TSFs across the state was established. The analysis highlighted that tailings from nickel and diamond operations, such as Mt Keith, Murrin Murrin, and Argyle, represent the most promising carbonation feedstocks due to their ultramafic and kimberlitic lithologies, which are rich in magnesium- and calcium-bearing silicates.

The review of pilot-scale mineral carbonation projects, including MCI Carbon, CARMEX, and Québec process, provided insight into how feedstock mineralogy, particle size, and process configuration influence CO₂ conversion efficiency. These findings were synthesised into a multi-criteria conceptual framework that enables the assessment of mine-waste suitability based on mineralogical, operational, and data-quality factors. The framework establishes a foundation for prioritising TSFs for further study and potential pilot-scale trials within WA.

Overall, this research confirms that WA hosts several large-scale mine wastes with favourable mineralogical characteristics for carbon dioxide removal through mineral carbonation. However, significant data gaps, particularly in mineralogical and geochemical parameters, limit the potential for quantitative evaluation. The framework developed through this study provides a pathway for integrating future datasets and guiding targeted site investigations, contributing to MRIWA's broader goal of promoting carbon-neutral mining and sustainable resource management in Western Australia.

6. Recommendations for further work

The outcomes of this study highlight both the strategic potential and critical limitations of the existing mine-waste data and research in advancing mineral carbonation within WA. Based on the findings from the database analysis and conceptual framework development, two primary sets of recommendations are proposed: (1) measures to improve existing databases to better support carbonation assessment, and (2) directions for future research to address the gaps in technical knowledge, process optimisation, and cost–benefit understanding of mine-waste carbonation.

6.1. Enhancing Existing Tailings Database

In this study, the TSFs hosted in mafic–ultramafic terrains across WA were identified and ranked by surface area as a proxy for storage capacity. The top 15 TSFs by area were associated with nine gold, three nickel, two iron, and one diamond operation, but compositional evidence indicates that nickel and diamond tailings are the more promising carbonation feedstocks, whereas gold and iron tailings tend to be silica-rich or Fe-oxide-dominated and therefore less reactive (Norouzpour et al., 2025). In WA, the largest single opportunity is the Mt Keith nickel TSF ($>15 \times 10^6 \text{ m}^2$), with Murrin Murrin and Argyle each exceeding $5 \times 10^6 \text{ m}^2$.

The analysis of POLYGON Dataset; MINEDEX (DMPE, 2025); Atlas of Australian Re-mining Potential (Geoscience Australia, 2021); and the Global Tailings Portal (Frank et al., 2021) demonstrated that while these repositories provide valuable information on site location, commodity, and general waste type, they lack the critical mineralogical and geochemical attributes required to evaluate carbonation suitability. However, when compared with the structured Chilean tailings database used by Marín et al. (2021), several areas for improvement are evident. In Chile, tailings information is maintained under a unified national inventory (SERNAGEOMIN) that integrates geochemical, volumetric, and spatial data, enabling the estimation of both sequestration potential and recovery of valuable metals. This approach allowed the authors to identify 27 major tailings accounting for over 90% of total stored tonnage, providing a solid baseline for mineral carbonation assessment and site prioritisation.

In contrast, Australian databases remain fragmented and primarily descriptive, lacking fields on mineralogical composition, Mg/Ca/Fe content, particle size, and tonnage of waste. Therefore, to enable quantitative assessment of CO₂ sequestration potential, it is recommended to build a public, queryable TSF database that records, at minimum: (i) chemistry (the 12 major oxides, trace metals, and REEs), (ii) tonnage, (iii) operational status (active/closed/rehab), and (iv) coordinates. Incorporating these parameters into a publicly available platform similar to the SERNAGEOMIN tailings inventory, would allow consistent screening of carbonation feedstocks and assist in spatial decision-making using multi-criteria tools such as TOPSIS or GIS-based analysis. Such improvements would make Australia's tailings datasets capable of supporting both academic research and pilot-scale feasibility evaluations for mineral carbonation, aligning with global best practices. In addition, comprehensive geochemical data for the TSFs would be directly useful not only for assessing

their potential for mineral carbonation but also for supporting critical-mineral recovery and environmental risk assessment.

6.2. Addressing Knowledge Gaps in Carbonation Potential of Tailings

Pilot-scale demonstrations underscore how engineered operating windows and hydrodynamics govern performance. In the Québec indirect aqueous pilot with real cement flue gas (12–20% CO₂), cumulative dissolved CO₂ reached 0.08–0.25 g g⁻¹ at 2–10 atm, with 25–33% of dissolved CO₂ precipitated as nesquehonite; CO₂ removal into solution was 90–96% at 2–4 atm (Kemache et al., 2017). In contrast, the MCI pilot on heat-activated serpentine reported ~33–35 wt% magnesite at 150 °C/150 bar with 0.64 M NaHCO₃, with yield gains over the laboratory system attributed to improved mixing (baffles, impeller, higher tip speed) (Benhelal et al., 2018). The CARMEX project showed that low-conversion aqueous routes can be net burdensome, whereas coupling mechanical exfoliation, high S/L (250 g L⁻¹), and high Mg conversion (≈79%) yields a 34% reduction in the climate-change indicator versus a no-capture baseline (Bodéan et al., 2014). Together, these results indicate that accelerated carbonation of WA nickel and diamond TSFs is technically plausible if operating conditions, hydrodynamics, and solids handling are co-optimised.

Despite substantial progress in pilot-scale demonstrations, significant knowledge gaps remain concerning the efficiency, process optimisation, and techno-economic performance of mineral carbonation using mine waste. The review of MCI, CARMEX, and the Québec pilot shows that carbonation efficiency is governed by a complex interplay between mineralogy, process configuration, and energy input. These findings confirm the technical feasibility of ex-situ mineral carbonation but also highlight important trade-offs between energy intensity, material handling, and CO₂ capture efficiency. To address these challenges and strengthen future research and implementation, several targeted areas of study are recommended. First, there is a need for standardised mineralogical characterisation of tailings to quantify reactive phases such as chlorite, serpentine, and olivine, which directly influence carbonation capacity. Consistent geochemical profiling across sites would improve comparative analyses and enable reliable modelling of sequestration potential.

Secondly, process integration studies should be prioritised to explore the possibility to pairing CO₂ sources such as power stations, cement kilns, and refineries with nearby TSFs to minimise transportation costs. This aligns with sustainable mine-closure and circular-economy objectives. In parallel, developing economic modelling frameworks, similar to the TOPSIS based approach applied in the Chilean study, can help prioritise tailings sites based on both sequestration potential and the recovery of valuable by-products such as Ni, Co, V, and REEs.

Additionally, lifecycle and cost–benefit analyses are necessary to evaluate energy requirements, reagent recycling potential, and the market viability of carbonate products, thereby establishing clearer pathways for industrial adoption. Finally, effective policy and data integration mechanisms must be established to promote open collaboration between mining companies, research institutions, and regulatory agencies. Such partnerships are essential for bridging the gap between research innovation and large-scale implementation, ensuring that mineral carbonation of mine waste becomes a practical and economically viable strategy for achieving net-zero mining operations.

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