ENVT5517 Assignment 3 - Remediation of Post-Mining Substrate Report

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1. Introduction

Australia's economy heavily relies on mining activities, with extensive operations across the country. Iron, extracted from ores such as magnetite and hematite, plays a critical role in steel manufacturing, which is essential for the construction development. In Western Australia(WA), a report from Australia's Economic Demonstrated Resources (EDR) indicated a total of 49,604 Mt of iron ore locates in the state (Summerfield, 2020). Iron production methods, including magnetic separation, electrostatic separation, flotation, and flocculation (Carmignano et al., 2021), generate large quantities of tailings, the by-products of extracting valuable materials. Long-term deposition of these tailings in dams alters the soil's characteristics(Sarathchandra et al., 2023). The high concentrations of heavy metals, along with extreme pH levels and electrical conductivity (EC), pose significant risks to human health, and to the flora and fauna in surrounding environments. It is estimated that 632 million tons of tailings were generated from iron ore mine in Australia (Carmignano et al., 2021), with around 2 tons of tailings generated from every ton of iron ore produced in WA (Thejas & Hossiney, 2022). Therefore, the large quantities of tailings must be effectively managed and rehabilitated with post-mining land use to prevent environmental contamination. Innovative rehabilitation strategies should be implemented to suit the tailings turning into the intended land uses with the analysis result of properties of tailings.

The objectives of this report are to: 1) analyse and interpret laboratory data on iron ore tailings; 2) decide the two most appropriate end land uses for the tailings; and 3) recommend management practices for the tailings site, aiming to achieve two final land-use options.

2. Methods

The magnetite iron ore tailings, including slurry and dry rejects. Slurry are primarily magnetite ore with banded iron formation and the rejects of the crushed material from the magnetic separation of iron processing are called dry rejects (Mather, 2024). It shows the complementary data for the slurry. They were collected from a flat site in the semi-arid, inland Pilbara region of northwest Western Australia. The site is in a valley between rocky hills. After collection, all samples were air-dried and sieved to a size of less than 2 mm. For total elemental, total carbon and nitrogen analysis, 5 g of the sieved sample from both materials was further grounded to a finer particle size before analysis. The samples were analysed with analytical methods listed in Table 1 to investigate the chemical and physical properties of the slurry and dry rejects of iron ore tailings. These experiments were conducted to identify the two most suitable end land uses for the post-mining rehabilitation of iron ore tailings site.

Table 1 The details of analytical method of iron ore tailings (Mather, 2024).

Properties	Measured method	Simplified procedure
pH	Soil solution (1:5 and 1:2) and the measurement of pH probe	The pH of both materials were measured using pH probes, with a soil-to-deionised (DI) water ratio of 1:5 and 1:2.
Electrical conductivity (EC)	Soil solution (1:5 and 1:2) and the measurement of EC probe	The EC of both materials were measured using pH probes, with a soil-to-deionised (DI) water ratio of 1:5 and 1:2.
Aggregate stability (slaking and dispersion)	Emerson's Dispersion Test	5-10 small aggregates of the samples were half filled with DI water in petri dishes and waited for different time (20 mins and 1 hour) to observe the cloudy situation of the solution and slaking or swelling particles respectively.
Total elements analysis	Heating process, dissolving of metal and the ICP-OES analysis instrument	The finely ground samples were combusted in compressed tin foil capsules using an autosampler. During combustion in the presence of oxygen, the carbon and nitrogen in the samples were converted into carbon dioxide and nitrogen oxides at 960 ℃.
Total carbon (TC) and total nitrogen(TN)	Dry Combustion and instrument Elementar Vario Macro Cube	The finely ground samples were heated using borate-based flux at 1000℃ and dissolved with 10% of hydraulic acid. The dissolved samples were analysed by ICP-OES with fusion method.
Particle size distribution and soil texture	Stoke's Law with gravitational sedimentation	The samples were accurately weighed and dried at 105℃ for 24 hours to determine moisture content. Other samples were weighed and dispersed using a dispersing agent in a milkshake cup. The solution was collected at specific time intervals after allowing the sediment to remain undisturbed. The collected samples were then dried overnight at 105℃. The dried sample weights were used to classify the soil texture.
Cation exchange capacity (CEC) and exchangeable cations	0.01 M silver-thiourea method	The CEC of the sample was measured using the silver-thiourea method to indicate the exchangeable cations in tailings. The finely ground samples were weighted accurately and extracted using (AgTU)+ and DI water respectively.
Mineral composition	X-ray diffraction (XRD)	The XRD was conducted by the UWA XRD Facility. The finely ground samples were analysed using the Aeris XRD Diffractometer in 45 minutes with generator settings (15Ma, 40kV).

3. Results

In case of electrical conductivity (EC) measured in a 1:5 ratio, one replicate in the dry rejects had a distinct value from another two replicates (Table 2), the mean EC for dry rejects is 638.35 ± 21.55 µS/cm after excluded the issued data. It might be due to technical errors. For pH and EC in the slurry measured at a 1:2 ratio, some inconsistencies might be due to the alkaline soil properties or technical errors.

Table 2 The original data of controversial data for pH and EC in iron ore tailings slurry.

Iron Ore Tailings	pH 1:2	pH 1:5	EC 1:2	EC 1:5
Slurry 1	9.35	9.6	763	492
Slurry 2	9.01	9.23	1486	616.8
Slurry 3	6.56	9.26	1603	659.9

**The word in red colour is the replicates that may be errors of lab analysis.*

The analysis of the iron ore tailings shows some differences between the slurry and dry rejects (Table 3). Both the slurry and dry rejects show alkaline properties, with pH values of 9.36 and 9.80, respectively, along with the saline features with EC values of 589.6 µS/cm for slurry and 195.7 µS/cm for dry rejects. According to the Emerson's Dispersion Test, both materials belong the second class, showing some dispersion and slaking aggregates. Total carbon content (TC) for both is unusually high, at 2.39% for slurry and 2.06% for dry rejects, compared to the typical values below 1%. However, total nitrogen (TN) remains very low at 0.02%.

Table 3 The comparison between the general and analysis properties of the iron ore tailings.

Properties	General Range (Sarathchandra et al., 2023)	Laboratory Data of Iron Ore Tailings	
		Slurry	Dry Rejects
Place	-	Pilbara, WA	Pilbara, WA
Type of iron ore	-	Magnetite	Magnetite
pH (1:5)	2-11(extreme range)	9.36±0.17	9.80±0.09
Electrical conductivity(µS/cm) (1:5)	<60000	589.6 ±71.2	195.7±12.7
Emerson class	-	2: Some dispersion/slaking	2: Some dispersion/cloudy
Total C % w/w	<1.0	2.39	2.060
Total N % w/w	<1.0	0.0223	0.01525
Particle distribution for sand (%)	-	58.02±1.77	87.34±0.38
Particle distribution for silt (%)	-	33.32±1.98	9.53±1.00
Particle distribution for clay (%)	-	8.66±0.21	3.13±0.62
Soil texture	-	Silty Loam	Loamy Sand

The soil texture of slurry and rejects are silty loam and loamy sand for dry rejects, with lower clay content and higher sand content. The cation exchange capacity (CEC) for both materials is low, 2.1 cmol(+)/kg(Table 4). Exchangeable calcium and potassium are also low, but exchangeable sodium is very high in slurry (2.1 cmol(+)/kg) and high in dry rejects (0.8 cmol(+)/kg)(Table 5).

Table 5 The comparison between the general and analysis CEC of the iron ore tailings.

CEC and Exchangeable Metal	General Range (Sarathchandra et al., 2023)	Slurry		Dry Rejects	
		Concentration (cmol(+)/kg)	Rating Levels	Concentration (cmol(+)/kg)	Rating Levels
CEC	-	2.1	Very low	2.1 ± 0.2	Very low
Ex-Ca	-	1.2	Very low	1.2	Very low
Ex-K	-	0.1	Very low	0.1	Very low
Ex-Mg	-	1.0	Low	0.7	Low
Ex-Na	-	2.1 ± 0.1	Very high	0.8	High

The elemental analysis (Table 6) reveals high concentrations of heavy metals such as iron, manganese, nickel, and chromium. Manganese levels in both the slurry (6079.4 mg/kg) and dry rejects (5066.3 mg/kg) exceed the health-based investigation levels (NEPC, 2013) for Residential A (3000 mg/kg) (Table 7). The Nickel concentrations of 149.3 mg/kg in the slurry and 182.1 mg/kg in the dry rejects exceed the default guideline value (21 mg/kg) and the additional upper guideline value (52 mg/kg) under the toxicant default guideline values for sediment quality (Australian and New Zealand Governments and Australian state and territory governments, 2018) (Figure 1).

The GAI (Geochemical Abundance Index) (INAP, 2010) results indicate that iron is highly concentrated, with values of 3.48 in the slurry, and manganese shows a GAI value of 4.05, indicating 24 to 48 times the median soil content for iron ore tailings (Table 8). Iron content is high at 20.9% in slurry and 22.8% in dry rejects, and total sulphur levels are 0.17% and 0.25% for both materials, respectively. Silicon content is approximately 23% in both materials. XRD analysis (Figure 2) shows that both materials are rich in quartz (slurry: 36.9 %; dry rejects: 41.9 %). Iron-bearing minerals are present at 33%, and the amounts of stilpnomelane and dolomite ($CaMg(CO_3)_2$) are found in both materials (Table 9).

Table 6 The total elemental analysis of the iron ore tailings.

Total Elements	Concentration of Elements	
	Slurry	Dry Rejects
Al (%)	1.43±0.02	1.46±0.01
Ba(mg/kg)	244.52±0.39	297.75±54.40
Ca (%)	1.06±0.01	0.96
Ce(mg/kg)	36.05±2.92	90.10±35.63
Co(mg/kg)	11.59±0.73	10.87±1.53
Cr(mg/kg)	89.74±2.53	155.09±4.06
Cu(mg/kg)	11.62±0.23	13.86±1.29
Fe (%)	20.89±0.13	22.75±0.30
K (%)	0.88±0.02	0.78
Mg (%)	1.89±0.05	1.55±0.02
Mn(mg/kg)	6079.44±172.35	5066.32±38.72
Mo (mg/kg)	2.52±0.12	4.21±0.35
Na (%)	0.15	0.23±0.08
Ni (mg/kg)	149.34±3.16	182.12±4.79
P (%)	0.12	0.11
S (%)	0.17	0.25±0.03
Si (%)	23.86±0.49	23.22±0.07
Sr (mg/kg)	29.83±0.69	27.86±0.45

Table 7 The comparison of laboratory data of metals with health-based investigation levels(NEPC, 2013).

	Lab Tailings (mg/kg)		Health-Based Investigation Levels			
Metal	Slurry	Dry rejects	Residential A	Residential B	Recreational C	Commercial/industrial D
Chromium (VI)	89.74	155.09	100	500	300	3600
Manganese	6079.44	5066.32	3800	14000	19000	60000
Nickel	149.34	182.12	400	1200	1200	6000

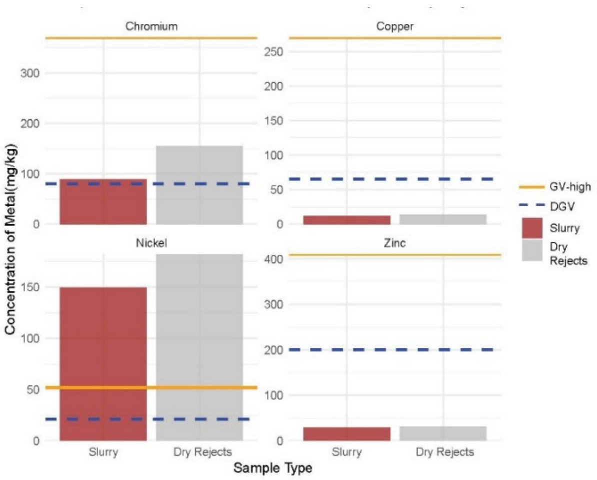

Figure 1 Histogram with the comparison between slurry and dry rejects of iron ore tailings with the guideline of toxicant in sediment. * *DGV means the default guideline value of the toxicant sediment quality; GV- high is the additional upper guideline value.*

Table 8 The GAI value of total elemental analysis of the iron ore tailings.

Total Elements	Slurry		Dry Rejects	
	GAI value	GAI range for further examination	GAI value	GAI range for further examination
Al (%)	0.13	<3	-2.90	<3
Ba(mg/kg)	0.33	<3	-1.62	<3
Ca (%)	0.47	<3	-1.09	<3
Ce(mg/kg)	0.48	<3	-1.06	<3
Co(mg/kg)	0.97	<3	-0.05	<3
Cr(mg/kg)	0.85	<3	-0.23	<3
Cu(mg/kg)	0.26	<3	-1.95	<3
Fe (%)	3.48	>3	1.80	<3
K (%)	0.42	<3	-1.25	<3
Mg (%)	2.52	<3	1.33	<3
Mn(mg/kg)	4.05	>3	2.02	<3
Mo (mg/kg)	0.84	<3	-0.25	<3
Na (%)	0.20	<3	-2.32	<3
Ni (mg/kg)	1.99	<3	0.99	<3
P (%)	0.001	<3	-13.28	<3
S (%)	1.62	<3	0.69	<3
Si (%)	0.48	<3	-1.05	<3
Sr (mg/kg)	0.08	<3	-3.65	<3

** A GAI of 3 represents 12-24 times median soil content; a GAI of 3 and above is considered as significant and may require further investigation (INAP, 2010) .*

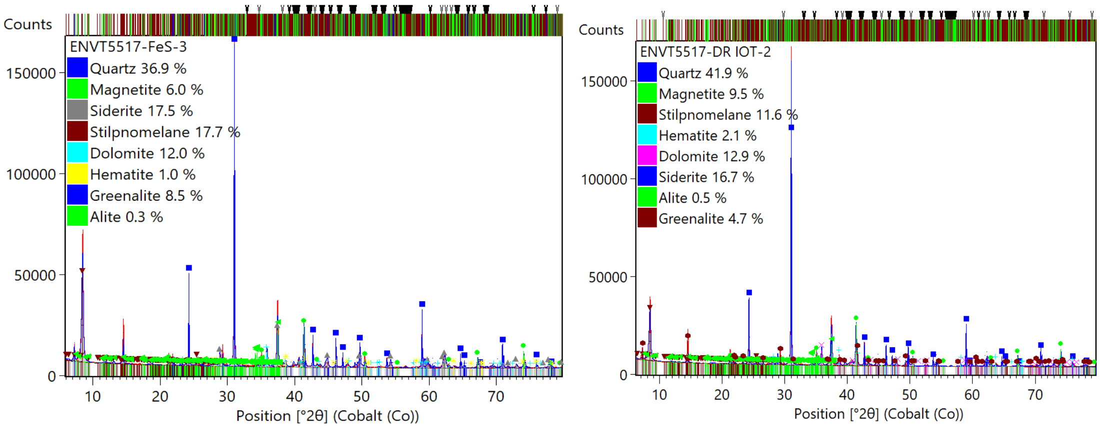

Figure 2 The XRD results with the mineral composition of slurry (left) and dry rejects(right) of tailings.

Table 9 The composition of iron-bearing minerals of tailings.

Mineral composition of iron chemicals	General Range (Sarathchandra et al., 2023)	Percentage of Mineral Composition (%)	
		Slurry	Dry Rejects
Greenalite (ferrous silicate)	-	8.5	4.7
Hematite (Fe_2O_3)	-	1.0	2.1
Magnetite (Fe_3O_4)	-	6.0	9.5
Siderite ($FeCO_3$)	-	17.5	16.7
Iron-bearing Minerals	-	33.0	33.0

4. Discussion

The chemical and biological properties of the slurry and dry rejects from iron ore tailings are mostly similar, aside from particle size distribution. Since dry rejects serve as complementary data for slurry, this discussion will focus on the slurry as representative of the iron ore tailings. The high manganese and iron content in the slurry (GAI >3) warrants further investigation through tests like humidity cell or column leach experiments(Green & Borden, 2011), as these elements may not be inert and could have environmental impacts. Since the higher total carbon content (TC) content is uncommon in iron ore tailings, the elevated percentage of siderite may explain the increased TC.

According to the Draft Guidance on Materials Characterisation Baseline Data Requirements for Mining Proposals, certain salt-tolerant plant species can thrive in salinity ranges between 400 and 1600 µS/m. However, higher concentrations of metals like manganese (exceeds the toxicity guideline of sediment) and iron combined with high alkalinity, low cation exchange capacity (CEC) and other soil conditions, may impact nutrient availability and soil fertility.

4.1 Post-Mining Land Use Choices

The closure of iron ore tailings should address simple and cost-effective land use options. Given the semi-arid climate of the Pilbara and the physical and chemical characteristics of the tailings, there are some limitations for end land use (Table 10). Native vegetation, less demanding in nutrient requirements, is a feasible option. It can adapt to semi-arid conditions after the amendments of the tailings that are being alkaline, saline, and low in CEC. Additionally, the flat and semi-arid of the site make it suitable for a light industrial zone with lower water usage, such as a solar panel assembly facility or small-scale solar panel production (Zenadrone, 2024). The lower requirements of environmental standards for light industrial zones, combined with the Pilbara's high solar irradiance (Solcast, 2023), make solar farms a promising option(Hunt et al., 2021). Solar projects as post mine land-use can reduce land-use conflicts and support decarbonisation efforts (Purtill, 2024). Thus, the choices for end land use of iron ore tailings are decided as native vegetation and light industrial zone, land uses with more environmental-friendly and economically beneficial.

Table 10 The inappropriate land uses with their rationale.

Land Use Options	Rationale
Golf Course and Cricket Oval	The inappropriate land use is because of the water scarcity in Pilbara. The maintenances of golf course and cricket oval need a lot of water, as a standard cricket oval need 160000 L to 300000 L water per week for maintenance (Water Dynamics, 2024).
Community Campground	The higher environmental requirements to develop community campground with water and waste management are more costly, as the rehabilitation of the iron ore tailings site needs to reach a standard suitable for human habitation compared to native vegetation and light industrial zone.
Cattle Pasture	The use of cattle pasture is not suitable for the iron ore tailings site due to the low cation exchange capacity (CEC), the very high level of exchangeable sodium, the lack of sufficient water resources for supporting grazing vegetation. While cattle pasture is common in the Pilbara region, despite the low nutrient levels, the high clay content in natural soils helps retain nutrients, preventing them from being easily lost (Ingram, 2001). However, the lower clay content and sodic features in the tailings, making cattle pasture land use less feasible.
Motocross Tracks	Due to the dust problem in semi-arid regions, limited economic opportunities in regional area and potential health risk to human from elevated concentrations of iron and manganese, the land use with motocross tracks is not feasible.

4.2 Recommendations of management practices to suit the end land uses

4.2.1 Native vegetation

For successful rehabilitation using native vegetation, soil stability with impact of the chemical and physical properties of the tailings (Table 11) to the limitations of native vegetation must be improved with in-situ rehabilitation. Amendments such as gypsum can increase CEC, lower pH, and reduce exchangeable sodium. The addition of organic matter and inoculation of soil microbes as soil aggregates form can help neutralise pH and enhance nutrient content (Wu et al., 2023). The following steps with the inoculation of pioneer plants as part of the phytostabilisation enhance water retention and reduce the concentration of heavy metals in the tailings(Sarathchandra et al., 2023; Wu et al., 2023). Phytoremediation techniques using pioneer plants with the selection of targeted species within a 100 km radius of the mine site from Pilbara(Erickson et al., 2017), such as *Triodia* grasslands, can adapt to the arid and semi-arid weather in Pilbara(Bellairs & Davidson, 1999). The monitoring is essential to ensure long-term rehabilitation success.

Table 11 The impact of the properties of tailings to the land use of native vegetation.

Chemical and physical properties of the iron ore tailings	The impact of the properties to the land use of native vegetation
Alkaline and Saline Environment	Plants and microbes are sensitive to the pH and EC conditions. The high pH and salinity environment need to be improved.
High level of Exchangeable Sodium	Low in nutrient contents and inhibit the soil infiltration.
Elevated heavy metals (manganese and iron)	The manganese and iron will hinder the establishment of vegetation with the plant growth progress(Coelho, 1990).
Soil Texture (silty loam)	The water retention and infiltration of the soil decrease the plant growth and lower clay content easily loss the nutrients.
Low CEC and low total nitrogen	Nutrient retaining problem for plant (Sarathchandra et al., 2023).
Native Vegetation Species	The native vegetation species adapt to the semi-arid weather but might be affected by the elevated metals.

4.2.2 Light industrial zone

The acceptable range of manganese and iron for light industrial land use is broader compared to native vegetation. However, manganese and iron can be effectively removed using aeration in a bioreactor containing limestone and pyrolusite (Jacob et al., 2019). The addition of gypsum and organic matter helps stabilise soil and decrease pH. Although human exposure is limited in a light industrial zone, appropriate water and waste management systems are essential to prevent metalliferous drainage.

Iron ore tailings can be reused for construction materials, such as concrete, which reduces costs and supports sustainable development (Shettima et al., 2016). From an economic and sustainability perspective, developing a solar farm is preferable to a solar panel assembly facility. Solar farms require less infrastructure, minimising landform changes and costs associated with extensive construction (Owen, 2018).

4.3 Impediments of the future rehabilitation process and their improvements

With future climate change projections for the Pilbara, annual precipitation is expected to decrease by 1.5%, and median annual evaporation will decline by 3.4% by 2030 under a high-emission scenario (DPIRD, 2024). The changing in climate could make the Pilbara aquifer more sensitive, increasing the risk of groundwater contamination from leaching. Water scarcity, pollution and soil erosion from weathering may become significant impediments for rehabilitation of iron ore tailings site. To enhance infiltration and extent water retention for vegetation establishment, a combination of land imprinting and bitumen emulsion crust can be applied (Dobrowolski, 2019). The runoff management can be improved, and phytoremediation can be further implemented to reduce the risks of soil erosion and pollution, respectively. Additionally, periodic monitoring of groundwater and vegetation is important to ensure the long-term success of rehabilitation efforts.

5. Conclusions

The chemical and physical properties of iron ore tailings show the high alkalinity, low nutrient content and retention, and elevated levels of manganese and iron levels, which require further investigation due to potential environmental impacts. Native vegetation and light industrial zone are identified as the most appropriate post-mining land uses for the tailings with semi-arid climate in Pilbara. The management actions with soil amendments and phytoremediation techniques can stabilise the soil and improve its conditions, supporting the development of native vegetation and light industrial zone. Alternatively, the development of solar industry as light industry is feasible due to Pilbara's high solar irradiance and minimal infrastructure required f.

However, future rehabilitation processes may face challenges from climate change with the risks of water scarcity and soil erosion. Improvements such as land imprinting, runoff management and regular environmental monitoring, will be essential to ensure the long-term success of rehabilitation projects.

6. References

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