

Laboratory Experiments to Evaluate the Potential Mobilization of Contaminants from Hard Rock Lithium Mining

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Executive Summary

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Background and Objective

The demand for lithium is projected to increase significantly this decade. This is primarily due to the increased utilization of lithium batteries that are now getting implemented to support transportation and store excess energy. The mining industry is responding through exploration and development to meet the forecasted demand. Pegmatite, which is a type of igneous rock, can contain significant amounts of lithium. Miners have tended to avoid pegmatite as the process is capital-intensive in comparison to other sources of lithium. The uptick in both price and demand for lithium have allowed some pegmatite sources to become economically viable for lithium extraction. Currently, the potential impacts of lithium mine tailings and waste rock from a pegmatite rock source on water quality are not fully documented. Reaching a scientific consensus on potential water quality impacts is important to understand given that the current demand for lithium stems from a clean and sustainable energy movement. The goal of this study is to provide laboratory-based water quality data and analysis for reference at projected pegmatite lithium sites in North Carolina. The Leaching Environmental Assessment Framework, also known as LEAF, was used to provide a more systematic testing methodology to evaluate the potential of contaminants mobilizing from hard rock lithium mining.

Sampling and Characterization

Sampling was conducted at a pegmatite lithium source in North Carolina. One groundwater and one surface water sample were collected on-site. These two samples were collected to understand baseline conditions. Solid samples of weathered ore, core and tailings were collected as well. Four samples were chosen for full chemistry: one rock core, one sand tailings, one tailings from density separation and one tailings from magnetic separation. A bulk characterization was conducted on these samples. Results of the bulk characterization were compared to average concentrations observed in the upper continental crust.

LEAF Test Methodology

The LEAF methodologies were created by the Environmental Protection Agency (EPA) to test water quality under controlled lab conditions that isolate variables known to significantly influence leaching in the environment. The LEAF 1316 methodology uses different water to rock ratios to understand the effects of dissolution on the samples. Ratios of 0.5, 1, 2, 5, and 10 (mL/g-dry) were used in this study. A lower liquid-to-solid ratio is meant to simulate a less porous environment. LEAF 1313 is designed to account for how varying levels of acidity affect leaching. Solid samples were tested in pH solutions of (± 0.5) of 2, 4, 5.5, 7, 8, 9, 10.5, 12 and 13. In both LEAF tests, samples were mixed in the different solutions for 24 hours before leachate was collected and measured. Results were compared to bulk characterization, institutional water quality standards and coal ash effluent data collected using LEAF.

Key Results

Water Quality On-site – 52 constituents were measured. Both the groundwater sample and surface water sample had concentrations of lithium that exceeded the US Geological Survey's Health-Based Screening Levels, which is an unenforceable drinking standard. The surface water sample also had a concentration of zinc that exceeded the EPA criterion continuous concentration, which is an unenforceable drinking standard. Lastly, both samples were moderately alkaline.

Bulk Characterization – All samples had a lower enrichment factor of arsenic, barium, lead and antimony relative to the upper continental crust. The tailings had a higher enrichment factor of beryllium and thallium relative to the upper continental crust, while the waste rock sample was lower. Copper and chromium had an opposite pattern where the waste rock enrichment factor was higher than the upper continental crust, while the tailings were lower. Uranium in the magnetic separate tailings was much higher than the other samples in this comparison.

Alkalinity – In LEAF 1316, all the samples in deionized water solution produced alkaline effluent ranging from a pH of approximately 7-10. In LEAF 1313, there was an observed buffer capacity of all samples between a pH of 6-10 in initial testing conditions between pH 4-10.5.

Percentage Leached from Bulk Solid – A lower pH resulted in a higher percentage of calcium, cobalt, cesium, manganese, strontium and zinc leaching. Uranium leached in both highly acidic and alkaline conditions. Lower liquid-to-solid ratios in the LEAF 1316 leached a higher percentage of cobalt, chromium, copper, iron, manganese, molybdenum, nickel, potassium, lead, uranium and zinc.

Comparison to Coal Ash and Water Quality Standards – In expected moderately alkaline conditions (pH 9), lithium effluent was not problematic in lab conditions, while coal ash effluent exceeded the maximum contaminant limits, an enforceable drinking water standard set by the EPA, of antimony, chromium, selenium and thallium. Coal ash effluent exceeded lithium rock effluent concentrations by a factor of 19 for antimony, 130 for chromium and 440 for selenium.

Main Takeaways

Mining inherently alters the surface area of rocks and exposure to water. The effluent produced from hard rock lithium tailings and waste rock in North Carolina is alkaline. This suggests that the potential for acid rock drainage is low. The buffering capacity of the lithium waste rock reduced mobilization of contaminants of concern. pH conditions outside of the buffer capacity should be avoided. Low liquid-to-solid conditions simulating low porosity should be avoided too given mobilization of contaminants including chromium, copper, lead and uranium increased. The mobilization of these contaminants in the lab setting does not mean they are problematic in field conditions. Further modeling at the site is needed to make any sort of inference about potential water contamination. However, in lab settings, there were conditions that promoted effluent concentrations of chromium, lead, uranium, beryllium, cadmium, antimony and thallium in the samples that exceeded drinking and ecological water quality standards. These constituents should be included in monitoring plans, although they were not problematic in the expected moderately alkaline (pH 9) condition. In expected alkaline conditions, there is less water contamination from hard rock lithium mine effluent than coal ash effluent.

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Abstract

Hard rock mining of lithium is projected to increase significantly over the next decade due to the demand for lithium in renewable energy. The potential impacts of lithium mine tailings and waste rock from a pegmatite source on water quality are not fully documented. Chemical interactions of lithium mine tailings and waste rock with meteoric water can promote leaching of contaminants from the residual rocks and potentially contaminate associated water. This study utilizes the Leaching Environmental Assessment Framework (LEAF) methods used by the US Environmental Protection Agency (EPA) to assess the potential of contaminants leaching from lithium tailings and possible impacts on water quality. Groundwater, surface water and waste rock samples from an undisclosed hard rock lithium mine site in North Carolina were collected. The results were compared to ecological and drinking water standards set by the EPA, US Geological Survey (USGS) and World Health Organization (WHO) as well as to the quality of effluents extracted from coal ash through the LEAF methodology. Results of the leaching experiments indicate that interactions between water and lithium tailings can cause the mobilization of metals and impact water quality. In all leaching scenarios, low liquid-solid (L/S) ratios caused higher mobilization of trace elements. The experimental acidity conditions affected mobilization of trace elements as well; under acidic conditions (lower than pH 4), the mobilization of beryllium, manganese, nickel, and cobalt are promoted, whereas under both acidic (lower than pH 4) and alkaline (greater than pH 10.5) conditions, zinc, lead, iron, aluminum, chromium, lithium, and uranium are mobilized into the effluents. Uranium in one sample leached 40.62% in pH 2, below the detection limit in pH 7 and 60.9% in pH 13 in comparison to the concentration of the bulk solid. Lead showed a similar pattern with one sample leaching 6.77% in initial pH of 2, below the detection limit in pH 7 and 3.54% in pH 12. These

results highlight the dependence of ambient acidity conditions on the mobilization of contaminants from lithium tailings solids. The LEAF tests indicated that the lithium waste rock samples all had a buffer capacity between pH 6-10 in testing conditions between pH 4-10.5 and produced slightly to moderately alkaline effluent between a pH of 7-10 in deionized water. Both the alkaline effluent and high buffering capacity observed in the LEAF tests suggests that the formation of acidic effluent and the potential for acid rock drainage is low. Alkaline water observed in the two samples taken on-site, i.e., one surface water sample and one groundwater sample, supports this finding. A comparison to the effluent chemistry generated from a LEAF experiment of coal ash reveals that industrial effluent from a lithium mine will have less of an impact on water quality than coal ash residuals. Under expected moderately alkaline conditions (pH 9) of both coal ash and lithium residual rock effluent, results showed that concentrations of coal ash effluent exceeded lithium rock effluent concentrations by a factor of 19 for antimony, 130 for chromium and 440 for selenium. This study highlights the need to monitor and manage the conditions at tailings and waste rock storage areas. There were L/S and acidity conditions in the lab setting where contaminants of concern including chromium, lead, uranium, beryllium, cadmium, antimony and thallium mobilized. Although the results of this study cannot be directly applied to field conditions, environmental managers should be aware of the conditions in which contaminants of concern mobilized in the lab setting. The main conclusions are that acid rock drainage is unlikely to occur given that the lithium residual rock samples all produced alkaline effluent, the buffer capacity of the lithium residual rock can reduce the risk of contamination associated with highly alkaline conditions, and lithium residual rock effluent in expected moderately alkaline conditions will have less of an impact than coal ash effluent on water quality.

Introduction

Background

The demand for lithium is projected to increase significantly over the next decade. McKinsey & Company, a leader in global management consulting, forecasts that the demand for lithium carbonate will increase from five hundred thousand metric tons (for 2021) to four million metric tons per year by 2030 (Azevedo et al., 2022). Traditionally, the primary use for lithium was in a variety of glass and porcelain products (Kavanagh et al., 2018). However, a new use case began emerging in the 1960s with research on lithium-ion batteries. The first commercialized lithium-ion battery made it to market in 1991 (Reddy et al., 2020). Demand for lithium shifted to supporting the batteries in consumer electronics. Improvements and innovation in battery technology are now expanding the application of lithium. Lithium batteries are now getting implemented to support transportation and store excess energy produced on the grid (Azevedo et al., 2022). Sourcing enough lithium to meet the exponential demand is going to be a challenge.

Exploitation of land for the purpose of extracting lithium is increasing to support the rising demand. There is a global rush to get mines operational in both developed and undeveloped countries (Reddy et al., 2020). Significant development is occurring in hard rock lithium mining in Australia and brines from salt lakes (salars) in what is being called the “Lithium Triangle” in South America, including Argentina, Chile and Bolivia. Lithium can be found in abundance globally; however, lithium is generally widely distributed and not found in large concentrations. High concentrations of lithium can typically be found in some granitic pegmatites and select closed basin brines (Kavanagh et al., 2018; Bradley et al., 2017). The operational costs of mining hard rock are an expensive endeavor. Previously uneconomic lithium deposits are becoming

viable options for extraction with recent price increases in lithium (Kavanagh et al., 2018). More high concentration hard rock mineral deposits are expected to come online as a result.

The opportunities presented from lithium extraction can help move society towards a sustainable future. Part of this mission demands that the extraction of lithium be conducted in a socially responsible and sustainable manner. The mining industry has a checkered past in this regard. Poorly managed mining operations have caused significant societal and environmental problems by harming forests, agricultural lands and water systems (Kavanagh et al., 2018). Evaluating the potential environmental impacts during the environmental permitting phase can allow companies to eliminate or mitigate any potential harm that can come from mining activities.

Mining companies are looking to extract lithium from the mineral spodumene. Spodumene is the primary lithium bearing mineral of interest and is found in select granitic pegmatites. The environmental effects of mining spodumene from pegmatites are currently not fully understood. A literature review on lithium extraction published in 2021 notes that there is a “dearth of studies focusing on the impacts of the pegmatites extraction phase as a stand-alone phase in relation to local communities, collective health and environment,” (Chaves et al., 2021). Academia is in a unique position to help lithium miners provide proper environmental management through research.

Communities near mining sites and companies sourcing material from lithium miners expect that the mining activities will not cause significant harm to the local water systems. One concern that is frequently cited in the mining world is acid rock drainage. This is a term coined for a process

where the dissolution of sulfide minerals forms sulfuric acid, decreasing pH which in turn can leach toxic metals from other minerals that can have a toxic effect on flora and fauna (Kavanagh et al., 2018). Most existing literature on the effects on water quality from lithium mining is focused on lithium-rich brines. Published literature on potential water quality impacts from mining lithium from pegmatites is limited.

There are currently only a few studies that have investigated the potential of water contamination from hard rock lithium mining, and these studies have shown contradictory results. One study investigated stagnant water at a pegmatite site in the Black Hills of South Dakota and found alkaline pH conditions ranging from a pH of 8-9 (Rahn et al., 1996). Another study investigated rock samples from the pegmatite and tailings at the Whabouchi mine site in Quebec, Canada and found that the samples produced circumneutral leachates between a pH of 6.5-8.5 (Roy et al., 2020). A study conducted in 2019 at a hard rock lithium mine site in Portugal examined how mining pegmatite could affect water quality by collecting associated surface water and groundwater samples. The samples were acidic with pH values ranging from 4.8 to 6.4. On the water constituent side, the mine site in Portugal did not find any evidence that mining activity altered water quality of the surrounding area, although the water samples had high chromium concentrations ranging from 8.8–98.6 $\mu\text{g/L}$ as well as lithium ranging from 6.9 and 74.1 $\mu\text{g/L}$ (Rodrigues et al., 2019). An environmental modeling attempt using sixty-four collected water samples taken from around the Jiajika lithium mine site in China similarly suggested that water quality is not affected by pegmatites (Yu & Yu, 2019). A different study conducted at the Jiajika lithium mine measuring surface water constituents found high levels of manganese with the highest concentration at 380 $\mu\text{g/L}$ and lead at 28.4 $\mu\text{g/L}$ (Juanqin et al., 2021). The potential for

contamination is noted in a literature review by Chaves et al. (2021) that cites an environmental impact study stating that pegmatite mining can lead to the “fragmentation of rocky materials, releasing immobilized elements into the water.” The use of the Leaching Environmental Assessment Framework (LEAF) in this master’s project is intended to provide a more systematic testing methodology to evaluate the potential of contaminants mobilization from hard rock lithium mining.

Objective

This study aims to evaluate the potential water quality impacts from hard rock lithium mining of pegmatite in North Carolina. This research will use the LEAF methodology recommended by the Environmental Protection Agency (EPA) to evaluate the magnitude of contaminants mobilizing under controlled laboratory conditions. Lithium mining companies will potentially use this information to supplement their waste rock and water monitoring and management strategies.

Research Disclosure

Research was conducted under the supervision of Professor Avner Vengosh’s water quality lab at Duke University and the guidance of an established lithium mining company. The intent of this research is to support best environmental practices and sustainability objectives.

LEAF Test Literature Review

The EPA originally developed LEAF to provide a set of methodologies that can help institutions effectively understand factors that can manipulate how solid substances leach into water sources. It has been included as a leaching test method under the US EPA hazardous waste policy SW-

846 (“SW-846 Test Method 1313”, 2017). The intention of developing these methodologies is to provide best management practices for the potential scenarios that can arise based on site-specific environmental conditions (Kosson et al., 2019). LEAF consists of four methodologies 1313, 1314, 1315 and 1316. These methodologies are designed to isolate variables like pH, liquid-to-solid ratios and how leaching is controlled, i.e., mass transport rates or chemical equilibrium (Kosson et al., 2019).

Each methodology went through a rigorous interlaboratory validation process before the EPA accepted the testing procedures. This laboratory validation process looked at effectiveness of these methodologies with inorganic constituents of potential concern (COPC) that includes both metals and radionuclides (Kosson et al., 2019). Between seven and ten laboratories participated in the validation process for each methodology. The interlaboratory process indicated that the methodologies produce precise results. Results from Method 1313 produced results where, “mean lab precision was 10% of the measured value within a laboratory and 26% between laboratories” (Kosson et al., 2019).

The design of the test is meant to provide consistent results across different industries and waste types. The EPA views LEAF as a, “consistent approach to estimate leaching of COPCs from a wide range of solid materials including as-generated wastes, treated wastes, e.g., solidified/stabilized soils and sediments, secondary materials, e.g., blast furnace slags, energy residuals, e.g., coal fly ash, air pollution control residues, industrial processing residuals, e.g., mining, and mineral processing wastes, and contaminated soil or sediments” (Kosson et al., 2019). These tests can help environmental managers in these different industries make

predictions, while accounting for potential changes to the environment. For example, the combination of Method 1313 and 1316 can help environmental managers estimate maximum potential leachate concentrations and understand the extent of the leaching over time (Kosson et al., 2019). The results can be applied across industries with different types of waste given that the LEAF methodology uses a laboratory setting to test for intrinsic leaching characteristics of solid materials. The results can be used with more localized and specific models like mass transport models to test for site-specific and industry-specific scenarios (Kosson et al., 2014).

The LEAF methodology is a relatively new testing method. Originally the LEAF methodology was developed so the EPA could address potential new regulations for Coal Combustion Residuals (CCR). There were other existing methodologies in place before LEAF like the Toxicity Characteristic Leaching Procedure (TCLP) and Synthetic Precipitation Leaching Procedure (SPLP) that has existed for many years. The problem with existing methodologies was that they were not designed to capture data for all potential field scenarios. For example, the TCLP methodology will tests samples at a couple of different acidities. It does not test across the spectrum of pH values, which can result in an understating or overstating of potential contaminants of concern if applied to an actual site location (Hattaway et al., 2013).

Concerns with LEAF also exist; however, the concerns focus more on the interpretation of the data. Some of these concerns revolve around a significantly larger volume of data produced. The reasoning is that the mass volume of data can result in incorrectly determining a worse-case scenario that does not reflect the actual field conditions as well as coming to conclusions when more evaluation is needed (Hattaway et al., 2013). Despite some of the raised concerns, LEAF

can provide valuable data when used correctly. Published field studies since the inception of LEAF have provided additional validation for the methodology.

The LEAF methodology has been used extensively to study coal. One study used both LEAF and TCLP to test leaching behavior of coal ash at five coal plants in China. Using both results from LEAF and TCLP allowed for a comparison of the two methodologies. The results of this study showed that many of the elements displayed similar results across the liquid-to-solid partitioning curve in pH dependent leaching tests despite the different mineralogical compositions of the coal ash at the plant sites (Zhao et al., 2020). This study observed results that validate the recommendations set forth by Hattaway et al. (2013) regarding using the LEAF test for coal combustion residuals. TCLP overestimated the leachability of hazardous elements like beryllium, boron, cobalt, nickel, copper, zinc, cadmium, antimony and uranium in the alkaline coal ash (Zhao et al., 2020). This is due to the TCLP not testing across the range of the pH spectrum. In the case of alkaline coal ash, the TCLP does not produce meaningful results since the methodology tests leaching in acidic conditions (Zhao et al., 2020). The result is a data set that shows a leaching potential that negates environmental factors that can make the test results highly improbable of actually occurring at the site.

Both LEAF methodology 1313 and 1316 were used at the coal ash sites in China. This study found that LEAF is better than TCLP at providing a comprehensive valuation of potential field results across the pH spectrum and the liquid-to-solid partitioning curve (Zhao et al., 2020). The expected neutral to alkaline field conditions at the coal ash sites were tested in the lab setting given that LEAF 1313 tests pH values ranging from 2 to 13. Environmental managers can make

better decisions with data from LEAF than the data from TCLP in this study as a result. These results validate LEAF for the original intended purpose of studying leachate from coal ash.

There is literature that expands the use of LEAF for other industrial purposes. In one study, researchers used LEAF to assess leaching risks at a copper and lead smelter site. The LEAF methodology was chosen because it can produce data that aligns with site-specific environmental conditions, and it can be incorporated into site-specific models like mass transport (Garrabrants et al., 2021). The data from LEAF can be combined with other site information like groundwater conductivity to form a holistic understanding of potential risks associated with water contamination. This study compared leaching of untreated soil at the site as well as a soil at the site treated with cement as a possible solidification/stabilization remediation technique. LEAF method 1313 was used to understand pH-dependent equilibrium leaching. Results of LEAF tests on the untreated and treated soils showed that leaching of constituents was significantly different between the two. For example, chromium and arsenic was reduced and displayed amphoteric behavior in the untreated soil, while the treated soil experienced a local maxima in the alkaline condition (Garrabrants et al., 2021). These observed differences in results can help environmental managers start assessing risk and potential effectiveness of waste disposal and site remediation plans. Incorporating these results with site-specific models can provide a detailed assessment that can reduce the uncertainty of how the leached constituents will affect the local environment.

LEAF testing is applicable to mine waste management and site remediation as well. One such study evaluated whether an underground gold mining site could be backfilled using cemented

paste tailings (Schafer, 2016). The concept implies that tailings from the mining activity will be pasted together using cement and then used to remediate the site. LEAF 1313 was one of the methods used to understand how the cemented paste tailings can potentially alter the local water quality. Using the LEAF 1313 methodology, the researchers sampled and tested original tailings, tailings cemented together and wall rock collected from the underground mine (Schafer, 2016). The LEAF tests proved successful in understanding the pH-dependent and L/S-dependent interactions that can come from using cemented paste tailings at this mine site.

The existing literature suggests that LEAF 1313 and 1316 is a practical methodology for conducting tests on leaching potential at hard rock lithium mine sites. LEAF testing provides data that can be used for site-specific environmental conditions. The significant amount of data that comes from LEAF testing allows for the data to be used in site models that can provide a holistic picture of potential water quality issues. Lastly, there have been successful studies conducting LEAF tests on mine tailings.

Materials & Methods

Sample Collection

Samples were collected from a pegmatite source rich in lithium at a mine site in North Carolina on October 7th, 2022. The location of this mine site will remain undisclosed for confidentiality purposes.

Water Sample Collection

Surface water and groundwater samples were collected using kits obtained through Professor Avner Vengosh's water quality lab. The test kits contained four separate bottles to measure trace metals, anions, alkalinity and isotopes. Approximately 500 mL of water were collected in total per sample. All water samples were collected in accordance with USGS sampling protocols (Wilde, 2006).

Rock Sample Collection

All solid samples collected came from different processing phases of ore to understand the potential water quality impacts that can come from a lithium mine site.

1. Weathered Rock - Three rock samples were collected from an outcrop at the mine, Weathered 1 (W1), Weathered 2 (W2) and Weathered 3 (W3). These samples were taken to help with the characterization of the material at the site. Outcrops provide insight on how natural weathering processes affect the minerals at the mine site.

2. Core – Three core samples were collected during a drilling program to obtain non-weathered samples of material to mimic the ore and waste rock that would be collected while mining. Core 1 (C1) is a pegmatite ore collected from the zone deemed economical to the lithium mine operation. The pegmatite sample was primarily used for site characterization purposes. Core 2 (C2) and Core 3 (C3) are potentially waste rock considered uneconomical to the operation that is disposed of immediately upon separation from pegmatite. Both waste rock samples (C2 & C3) were studied more intensively than C1 as the waste at a mine site is what has the potential to pose environmental and health concerns.

3. Tailings – Multiple stages of processing occur to separate the lithium in the pegmatite from other mineral constituents. Understanding the potential risks from waste coming from the pegmatite zone is also essential to understanding potential environmental and health impacts. Tailings 1 (T1) and Tailings 2 (T2) separated material using magnetic fraction. The difference between the two samples is T2 magnetic separates are larger in size. Tailings 3 (T3) are from a lithium concentrate. Tailings 4 (T4) and Tailings 5 (T5) were separated based on density. T4 is a second pass through the density separation process, and T5 is a third pass through the process. The last sample is taken from a dried sand tailings pond on-site (STP). STP represents a collection of the tailings as this is an example of a final disposal site.

Experimental

Solid Sample Prep

All rock samples were reduced in size to a fine powder and dried in an oven at 45 degrees Celsius for 24 hours before any tests began.

Bulk Characterization

All solid rock samples were tested to understand the chemical composition. A two-day digestion period took place using HNO₃ and HF. During this time, the samples were placed on a hot plate set at 105 degrees Celsius. These samples were then diluted. An internal standard was added to all samples for quality assurance. Additionally, a quality control was issued in this process using a solid sample acquired from the USGS identified as USGS G-2, which is a granite sample used as both a standard of accurate results and comparison. The samples were acidified using HNO₃ for storage purposes until they could be run through the Inductively Coupled Plasma Mass Spectrometer (ICP-MS) for chemical constituent analysis.

LEAF Test Considerations

C2, C3, T2, T4 and STP were picked for further study. C2 and C3 were blended at a 1:1 ratio for this part of the testing under the sample ID C23. These samples were selected because they represent the different stages of waste creation during the mining process.

LEAF 1313 Test Prep

LEAF 1313, “is designed to provide aqueous extracts representing the liquid-solid partitioning (LSP) curve as a function of pH,” (“SW-846 Test Method 1313”, 2017). Pre-test titration was performed to test each sample at a pH value (± 0.5) of 2, 4, 5.5, 7, 8, 9, 10.5, 12 and 13.

Reaching these values was achieved using 0.01M HNO₃ and 0.01M NaOH. For control purposes, each sample had a deionized water blank, NaOH solution blank and HNO₃ solution blank.

Twelve high density polyethylene (HDPE) bottles were used in total per sample. A liquid-to-solid ratio of 10:1 (mL/g-dry) was used for this method. Approximately 2 grams of solid sample was measured and mixed with varying pH values at the 10:1 liquid-to-solid ratio.

LEAF 1316 Test Prep

Leaf 1316, “is designed to provide the liquid-solid partitioning (LSP) of inorganic constituents, e.g., metals and radionuclides, and non-volatile organic constituents, e.g., polycyclic aromatic hydrocarbons (PAHs) and dissolved organic carbon, at the natural pH of the solid material as a function of liquid-to-solid ratio (L/S) under conditions that approach liquid-solid chemical equilibrium,” (“SW-846 Test Method 1316”, 2017). The L/S ratios of 0.5, 1, 2, 5, and 10 (mL/g-dry) were used. These ratios translated into 40, 20, 10, 4 and 2 grams of solid sample in 20 milliliters of deionized water. In addition to providing information on equilibrium conditions at

the natural pH of the sample, the ratios also simulate different porosity and permeability conditions. For example, a low ratio is meant to simulate low pore space or low permeability conditions. To ensure quality control, four blanks of deionized water were used.

LEAF 1313 and 1316 Testing

The prepped HDPE bottles from both LEAF methodologies were tested the same way. The bottles were placed on a shaker for 24 hours in room temperature conditions. Immediately after the 24 hours of shaking, the bottles were moved into a centrifuge to separate the solids and liquids. The centrifuge allowed for leachate to be extracted from the liquid using a metal-free syringes. A 0.45- μm syringe filter was attached to the syringes to ensure no solid particulates were extracted. The leachate from each sample was placed into test tubes. Final pH levels of the samples were measured immediately after using a pre-calibrated pH probe. Following pH measurements, HNO_3 was added to the test tubes for storage. A final dilution took place where 5 millimeters of each sample was mixed with 15 milliliters of deionized water. An internal standard was then added for quality control. This remaining leachate was run through the ICP-MS for chemical constituent analysis.

Data Analysis

The raw data collected from the bulk characterization and LEAF tests was inputted into excel sheets. This data was normalized to $\mu\text{g/L}$ and mg/kg . Method Detection Limits (MDL) were calculated using procedures set by the EPA, i.e., the concentration equivalent to three times the standard deviation of replicate instrumental measurements of spiked blanks (“Definition and Procedure”, 2016). These excel sheets were inputted into R for analysis and graphical purposes.

1. Compare bulk characterization at different stages of mine waste processing

Analysis on initial concentrations provides insights on the mineralization of the property as well as what chemical constituents can possibly leach into the environment.

2. Percentage leached from LEAF 1313 and 1316 in comparison to bulk characterization

This comparison is designed to show how readily available the chemical constituents are in terms of the potential to enter the environment.

3. Final pH levels and constituent concentrations of LEAF 1313 and 1316 compared with ecological and drinking standards

The comparison to water standards is meant to indicate if there are any constituents that could be a potential concern if proper mitigation steps are not taken. The EPA's Maximum Contaminant Levels (MCL), World Health Organization (WHO) Guideline Values (GLV) and the United States Geological Service's (USGS) Health-Based Screening Levels (HBSL) are drinking water standards designed to protect human health (World Health Organization, 2022; USGS Health, 2019; National Primary, 2023). The EPA's Criterion Continuous Concentration (CCC) is an ecological standard estimating, "the highest concentration of a material in ambient water to which an aquatic community can be exposed indefinitely without resulting in an unacceptable adverse effect ("Supplemental Module: Aquatic Life Criteria", 2022).

(ppb)	USEPA MCL	USEPA CCC	WHO GLV	USGS HBSL	MDL
Li				10	23
Be	4				
B			2400	5000	72
Al				6000	36
Cr	100	11	50	20	<1
Mn			400	300	1
Fe		1000		4000	29
Co				2	<1
Ni		52	70	100	3
Cu	1300		2000		23
Zn		120		2000	41
As	10	150	10		<1
Se	50		40		9
Sr				4000	8
Mo				30	17
Ag				100	<1
Cd	5	0.72	3		<1
Sb	6		20		<1
Ba	2000		700		3
Tl	2				<1
Pb	15	2.5	10		<1
U	30		30		<1

Table 1 - Elements measured in the study with ecological and drinking water standards are listed. Concentrations are measured in ppb. USEPA MCL, WHO GLV and USGS HBSL are drinking water standards (World Health Organization, 2022; USGS Health, 2019; (National Primary, 2023). USEPA CCC is an ecological water standard (“Supplemental Module: Aquatic Life Criteria”, 2022). Minimum Detection Limit (MDL) was calculated using the concentration equivalent to three times the standard deviation of replicate instrumental measurements of spiked blanks (“Definition and Procedure”, 2016).

4. Compare LEAF results to actual observed groundwater and surface water at mine site

This comparison provides insight on the water quality naturally occurring at the mine site. There is the potential to match current conditions to some of the results observed in LEAF 1313 and 1316. Completely different testing results to the local water constituents could provide meaningful insights as well.

5. Coal mining LEAF results compared with lithium mining LEAF results

Data from Wang et. al. (n.d.) on leaching from coal ash was obtained. Coal ash taken from North Carolina identified as Bull Run Fly Ash (BRFA) was used in this comparison. Analysis to see

differences in leachate can provide insight on how environmental impacts from mining would change if energy became clean and mining focused on metals supporting clean energy.

Results

Current Water Quality On-site

The groundwater and surface water quality on-site meets enforceable water quality standards set by the US government. USGS HBSL standards set for lithium are exceeded at the site given the geologic pegmatite anomaly at the site. Zinc in the groundwater is slightly above recommended ecological standards set by the EPA, but the surface water did not breach the recommended level (See Table 2). Table 3 provides concentrations of all 52 constituents measured.

The groundwater had a measured pH of 9.34, and the surface water measured a pH of 8.39.

These measurements indicate alkaline field conditions at the mine site. LEAF 1313 accounts for pH values between 2-13. These field conditions suggests that slightly alkaline conditions are likely to better predict leaching behavior at this specific mine site.

Water Standards Comparison to Field Data	pH	Li (ppb)	Zn (ppb)
USEPA CCC		-	120
USGS HBSL		10	-
Groundwater Sample (1)	9.34	46,764	166
Surface Water Sample (1)	8.39	816	117

Table 2 - Comparison of water standards to groundwater and surface water samples at field site. Concentrations are in parts per billion (ppb). BDL stands for below detection limit.

Site Water Quality Data Set			
		Groundwater	Surface Water
	pH	9.34	8.39
Li	µg/L	46,764	816
Be	µg/L	<1	<1
B	µg/L	51	11
Na	µg/L	38,976	10,344
Mg	µg/L	130	11,886
Al	µg/L	407	18
P	µg/L	45,738	20
K	µg/L	465	4,570
Ca	µg/L	1,106	42,756
Sc	µg/L	<1	<1
V	µg/L	1	<1
Cr	µg/L	11	7
Mn	µg/L	11	8
Fe	µg/L	96	45
Co	µg/L	<1	<1
Ni	µg/L	6	5
Cu	µg/L	5	1
Zn	µg/L	166	117
Ga	µg/L	1	bdl - <1
Ge	µg/L	1	<1
As	µg/L	1	7
Se	µg/L	bdl - <9	<1
Rb	µg/L	8	42
Sr	µg/L	3	155
Y	µg/L	<1	<1
Nb	µg/L	<1	bdl
Mo	µg/L	20	<1
Pd	µg/L	bdl	<1
Ag	µg/L	<1	bdl - <1
Cd	µg/L	<1	<1
Sb	µg/L	<1	<1
Te	µg/L	bdl	bdl
Cs	µg/L	21	68
Ba	µg/L	2	1
La	µg/L	<1	bdl - <1
Ce	µg/L	<1	bdl - <1
Pr	µg/L	bdl - <1	bdl - <1
Nd	µg/L	<1	bdl - <1
Sm	µg/L	bdl - <1	bdl - <1
Eu	µg/L	bdl - <1	bdl - <1
Gd	µg/L	bdl - <1	bdl - <1
Tb	µg/L	bdl - <1	bdl - <1
Dy	µg/L	bdl - <1	bdl - <1
Ho	µg/L	bdl - <1	bdl - <1
Er	µg/L	bdl - <1	bdl - <1
Yb	µg/L	bdl - <1	bdl - <1
Lu	µg/L	bdl - <1	bdl - <1
Ta	µg/L	<1	bdl
Tl	µg/L	<1	bdl - <1
Pb	µg/L	1	<1
Th	µg/L	<1	bdl - <1
U	µg/L	14	1

Table 3 – All 52 measured constituent concentrations of groundwater (1 sample in total) and surface water (1 sample in total) at field site. Concentrations are in parts per billion (ppb). BDL stands for below detection limit. Values next to BDL reflect the Minimum Detection Limit (MDL). MDL was calculated using the concentration equivalent to three times the standard deviation of replicate instrumental measurements of spiked blanks (“Definition and Procedure”, 2016).

Bulk Characterization

All solid rock samples were tested for bulk characterization. This analysis focuses on the four samples (T2, T4, STP, C23) used for LEAF testing to understand the full chemistry of these samples. Bulk concentrations of elements with MCL standards in this study were compared to a study by Rudnick and Gao (2014) that measured elemental concentrations in the upper continental crust. This comparison displayed in Chart 1 and Table 4 compares the samples to the upper continental crust using an enrichment factor that calculates the difference as a ratio. Ratios were calculated by dividing the bulk concentrations of lithium samples by the average concentration observed in the upper continental crust.

C23, STP, T2 and T4 all had a lower enrichment factor of arsenic (0.03-0.23), barium (<0.01-0.1), lead (0.1-0.8) and antimony (0.07-0.6) relative to the upper continental crust. The tailings (STP, T2, T4) had a higher enrichment factor relative to the upper continental crust of beryllium all between 8-53, while waste rock sample (C23) was lower with an enrichment factor of 0.55. Thallium showed a similar pattern with the enrichment factor of tailings (STP, T2, T4) ranging between 1-8 and waste rock sample (C23) lower relative to the upper continental crust with a factor of 0.55. The enrichment factor of chromium was higher relative to the upper continental crust for waste rock sample (C23) with 1.55, while tailings (T2, T4, STP) were lower with an enrichment factor between 0.01-0.5. Copper showed a similar pattern relative to the upper continental crust with waste rock sample (C23) at 1.89 and tailings samples (T2, T4, STP) ranging from 0.01-0.9. The enrichment factor of cadmium was mixed between samples. T2 and C23 were higher with 9.96 and 2.61, respectively, while STP was lower than 0.01 and T4 was 0.61. Selenium also showed mixed enrichment factor results with T2, STP and C23 ranging

between approximately 2-4, and T4 was lower relative to the continental crust average with a factor of 0.31. Uranium enrichment factor results were mixed as well. T2 was much higher at a factor of approximately 25. T4 was approximately the same relative to the upper continental crust at a factor of 1.07. STP and C23 were lower with a factor of 0.51 and 0.24, respectively.

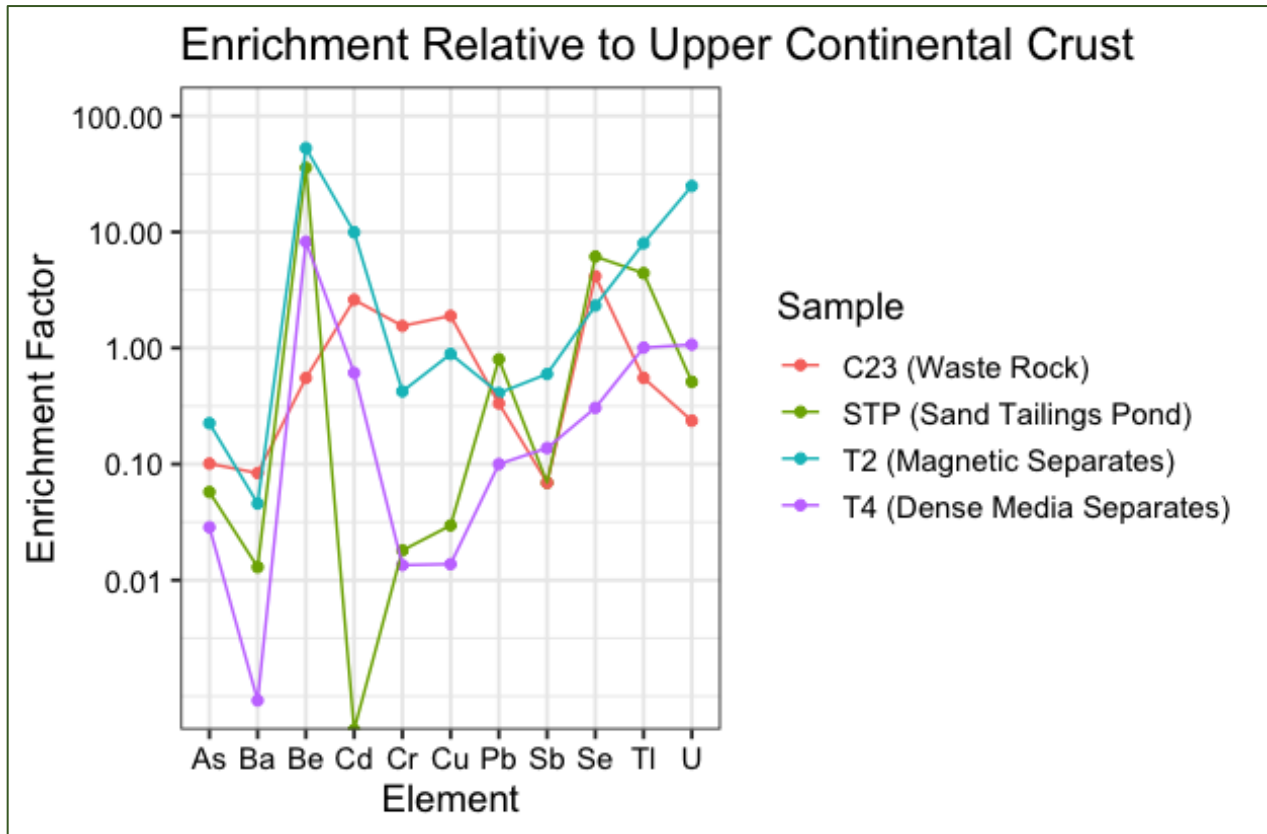


Chart 1 - Bulk concentrations of tailings were measured. The chart compares observed concentrations of elements with MCL standards to averages observed in the upper continental crust (Rudnick and Gao, 2014). Results are displayed as an enrichment factor, which was calculated as a ratio between bulk samples to upper continental crust averages.

Enrichment Factor of Lithium Bulk Concentrations to Upper Continental Crust Averages											
Sample	Be	Cr	Cu	As	Se	Cd	Sb	Ba	Tl	Pb	U
T2 (Magnetic Separates)	52.86	0.42	0.89	0.23	2.32	9.96	0.60	0.05	8.00	0.41	24.93
T4 (Dense Media Separates)	8.24	0.01	0.01	0.03	0.31	0.61	0.14	0.00	1.01	0.10	1.07
STP (Sand Tailings Pond)	35.76	0.02	0.03	0.06	6.14	0.00	0.07	0.01	4.42	0.80	0.51
C23 - Waste Rock	0.55	1.55	1.89	0.10	4.16	2.61	0.07	0.08	0.55	0.33	0.24

Table 4 – Displays enrichment factor values between bulk concentrations of lithium mine samples to upper continental crust averages.

LEAF Results

LEAF 1313 pH

A comparison of the initial pH with the final pH shows that all the solid samples produce alkaline effluents. The effect on lower initially tested pH levels ranging from 2-4 resulted in a higher final pH. T2 and T4 had final pH readings over 8.5 in the initial pH 4 testing condition. All samples in solution reached a final pH buffer state between 6-10 at initial pH testing values between 4-10.5. The buffer capacity of the final pH in STP was in the range of 6-7.5, whereas the other solid samples buffer capacity in the final pH ranged from 7.5 to 10. A steep rise in final pH occurred from initial pH solution values between 10.5-12. The samples produced alkaline water that was less basic than the initial pH test value of 13, so the final value never reached or went higher than this initial tested pH value of 13. Chart 2 shows that the rise in the final pH occurs mostly in T4>T2>C23>STP.

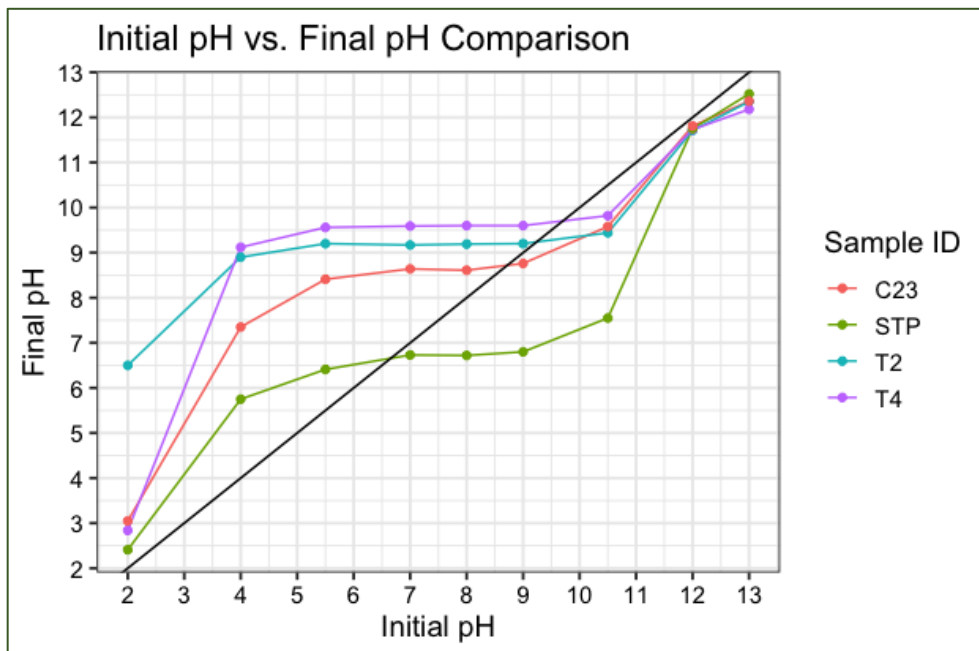


Chart 2 - The chart compares the initial pH of the solution (+/- 0.5) with the final testing pH. The comparison highlights how the lithium samples may influence pH levels. The black line represents a 1:1 slope to indicate whether the final solution is more acidic or alkaline than the initial test solution.

LEAF 1313 Leaching Percentage

The LEAF 1313 methodology can help environmental managers interpret how external environmental factors can possibly affect the solubility of the samples through manipulation of pH levels. Leaching percentage was calculated by dividing the LEAF concentrations in mg/kg to the concentration of the bulk characterization in mg/kg. An important observation in this comparison is that extreme pH values whether acidic or basic can have a significant effect on the solubility and mobilization of some of the constituents present in the bulk characterization. The results show that the leaching percentages differ between samples, but the mobilization patterns of each constituent in the varying acidities are similar (See Chart 3 and 4).

A lower pH resulted in a higher percentage of calcium, cobalt, cesium, manganese, strontium and zinc leaching. Calcium in STP leached 36.83% at an initial pH test value of 2, while only leaching 0.39% at an initial pH of 7 and 0.65% at an initial pH testing value of 13. Cobalt in T4 leached 100.68% in an initial pH solution of 2, 3.91% in pH 7, and 0.23% in pH 13. Slightly above 100% is a valid possibility in this calculation given that different sample of T4 was used in the bulk characterization and LEAF test processes. Cesium in C23 leached 17.34% in pH 2, 1.85% in pH 7 and 2.68% in pH 13. Manganese in T4 leached 28% in pH 2, 0.16% in pH 7 and 0.07% in pH 13. Strontium in T4 leached 14.45% in pH 2, BDL in pH 7, and BDL in pH 13. Zinc in STP leached 38.66% in pH 2, 0.81% in pH 7 and 3.62% in pH 13 (See Chart 3).

Phosphorous, uranium, lead and had a higher percentage of leaching at both pH extremes. Phosphorous in T4 leached 26.73% in pH 2 and 3.45% in pH 7, while STP leached 12.91% in a pH 13. In STP the pH rose in alkaline pH 13 conditions to 12.91%. Uranium in STP leached

40.62% in pH 2, BDL in pH 7 and 60.9% in pH 13. Lead in STP leached 6.77% in initial pH of 2, BDL in pH 7 and 3.54% in pH 12 (See Chart 3).

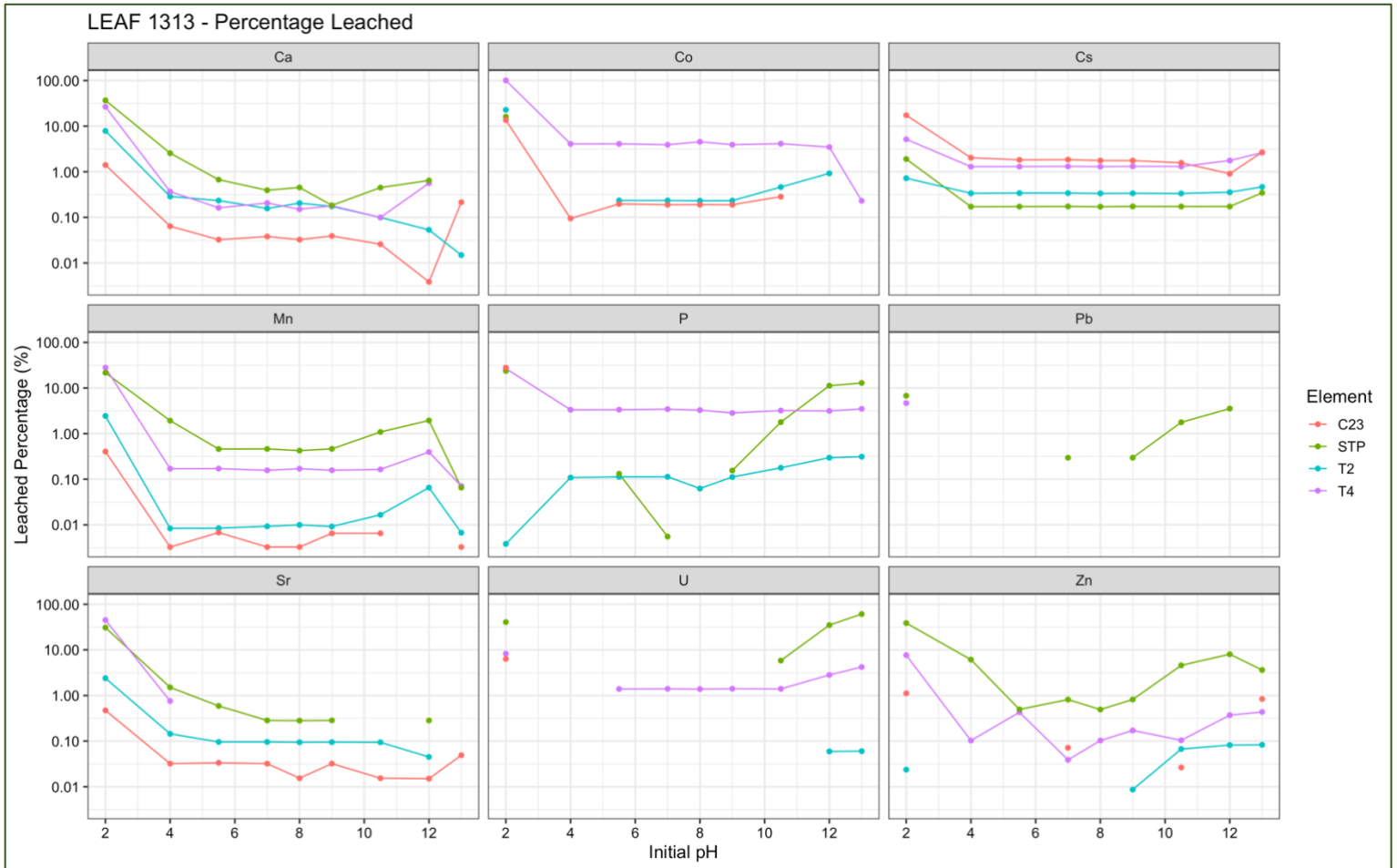


Chart 3 - Shows the percentage leached into solution from samples C23, STP, T2 and T4 during the LEAF 1313 experiment. Concentrations below the detection limit (BDL) in LEAF 1313 were not plotted in this chart as observed by line breaks.

LEAF 1313 Leaching Concentrations

Under specific low (below pH of 4) and high (above pH of 10.5) leaching conditions, aluminum, chromium, lithium, lead, uranium, and zinc concentrations in the effluents exceeded or were near exceeding the threshold values of the water quality standards (See Chart 4). Aluminum exceeded

HBSL when the initial pH value was lower than 4 and greater than 10.5. All tailings (T2, T4, STP) showed exceedance of MCL and GLV at initial pH test greater than 10.5; T2 and T4 also exceeded the CCC standard in this condition. The data shows that under a pH value of 2 the Al contents are high in effluents extracted from T4 and STP samples. Leaching of chromium was high at a very low pH testing value of 2. Chromium in effluents extracted from STP and C23 exceeded the CCC, respectively. C23 also exceeded the GLV standard in this condition as well. Lithium in effluents extracted from all samples across all initial pH value tests exceeded the HBSL. Lead was mobilized in STP, and effluents exceeded both MCL and GLV standards under pH conditions lower than 4 and greater than 10.5. Uranium in effluents extracted from STP exceeded both the MCL and GLV standards at pH test values lower than 3 and greater than 12. Zinc exceeded the CCC standard in effluent extracted from STP and T4 at a low pH test value of 2.

In acidic conditions below a pH of 4, beryllium, cobalt, iron, manganese and nickel increased in availability and exceeded water quality standards (See Chart 5). Beryllium exceeded the MCL at a low initial pH test of 2 in effluents extracted from C23, STP and T4. Cobalt effluent exceeded HBSL guidance in all samples and initial pH testing conditions, although mobilization was greater in pH conditions lower than 4. Iron effluents from C23 and T4 exceeded both MCL and GLV in low initial pH conditions of 4 and below. STP effluent also exceeded the MCL at an initial acidic pH test of 2. C23 was consistently close to the MCL threshold at all testing values above 4. Iron effluent extracted from STP in initial pH tests greater than or equal to 9 exceeded both MCL and GLV. T2 and T4 effluent exceeded the MCL standard at an initial testing value of 12. Manganese increased in availability in initial pH solution lower than 4 with effluent from

C23, T4 and T2 exceeding the GSV and HBSL standard. Nickel concentrations in effluent from C23 at a low initial pH value of 2 exceeded the CCC and GLV standard.

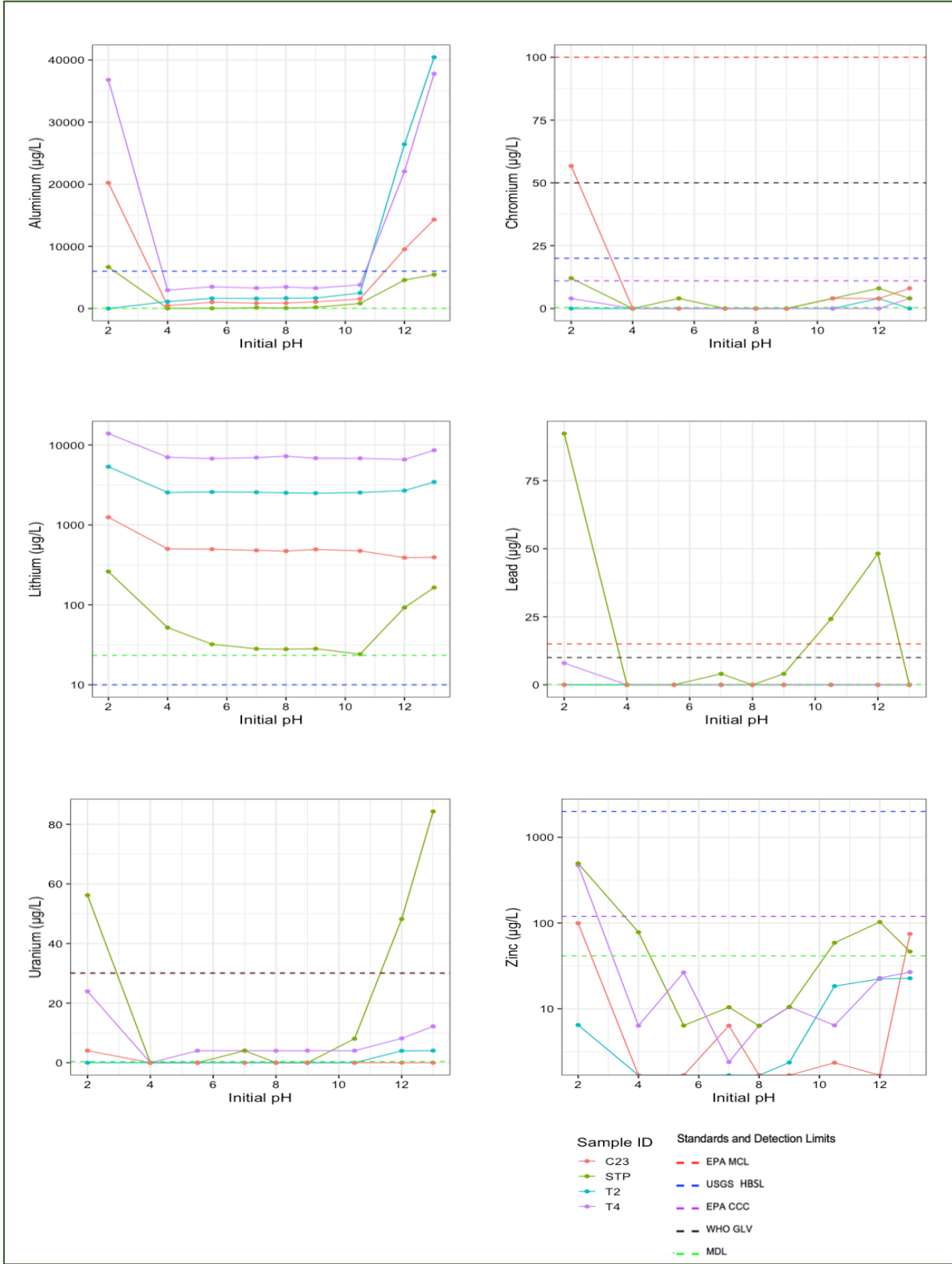


Chart 4 - LEAF 1313 results for aluminum, chromium, lithium, lead, uranium, zinc. Leachate increased in both alkaline and acidic conditions. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

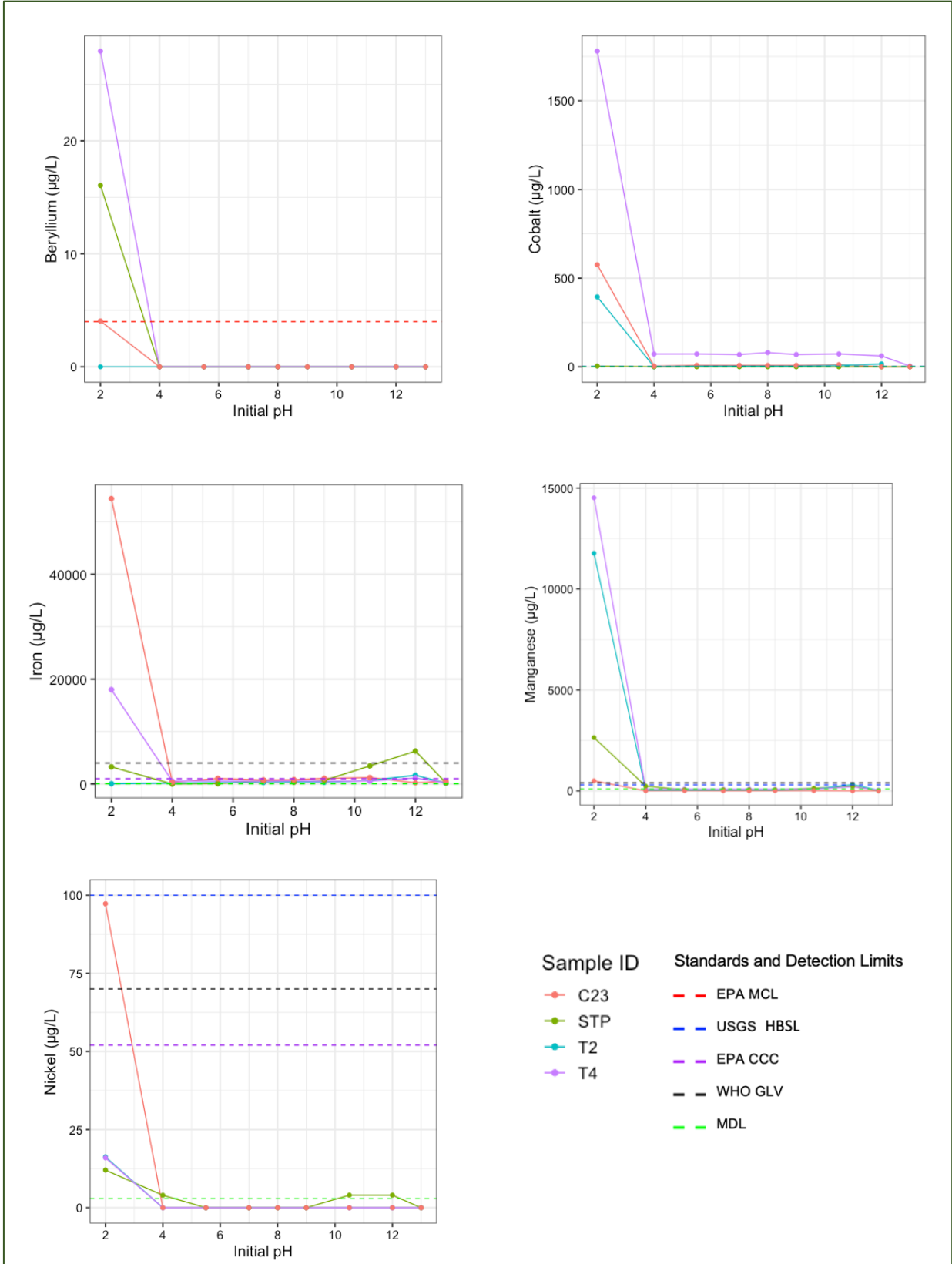


Chart 5 - LEAF 1313 results for beryllium, cobalt, iron, manganese and nickel. Leachate increased in acidic conditions. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

LEAF 1316 pH

The purpose of the 1316 LEAF methodology is to understand how soluble the minerals are in water. A key finding is that all tested sample turned the deionized water alkaline as noted by the final pH reading, and this was both consistent and stable throughout the varying liquid-to-solid ratios (See Chart 6). The alkaline conditions fostered by the waste rock and tailings should be noted since pH level can affect constituent mobilization and induce leaching of various minerals depending on the local environmental conditions and how the water is managed. The experimental data is consistent with the field data results that showed relatively high pH in the local groundwater from the mine site. The high buffering capacity of the rocks used in the LEAF experiments infers that the potential of forming high acidify effluents, i.e., acid rock drainage, from the lithium mining rocks is low.

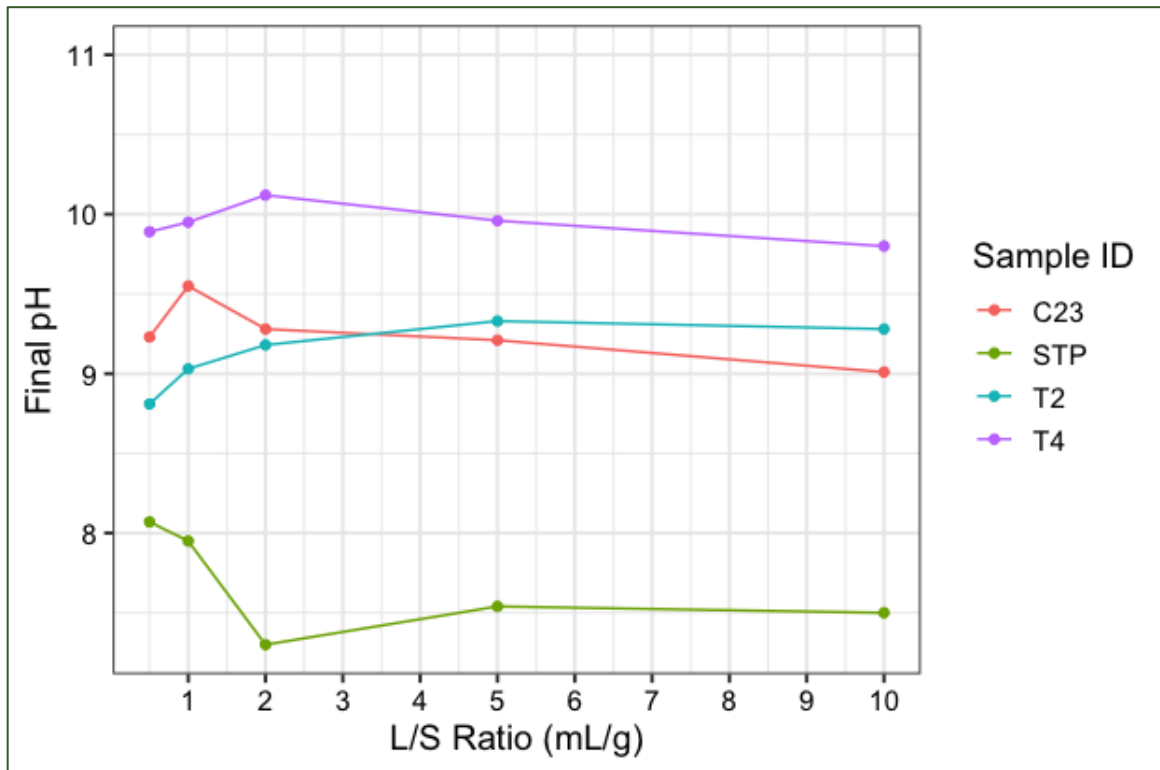


Chart 6 - Shows how the pH of deionized water changed after LEAF 1316 experimentation.

LEAF 1316 Leaching Percentage

Lower liquid-to-solid ratios in the LEAF 1316 methodology consistently leached a higher percentage of constituents. This is likely because lower ratios have greater amount of material to react with the water, so dilution is a less significant factor. Leaching percentage was once again calculated by dividing the LEAF concentrations to the bulk characterization concentrations.

The sand tailings pond (STP) that is essentially a mixture of all discarded rock waste showed that a high percentage of cobalt, chromium, copper, iron, manganese, molybdenum, nickel, phosphorous, lead, uranium and zinc leached indicating that these elements are soluble and can mobilize under the right conditions. Cobalt leached 18.19% in a L/S ratio of 0.5 and BDL in a L/S ratio of 10. Chromium leached 14.12% in a L/S ratio of 0.5 and 2.36% in a L/S ratio of 10. Copper leached 42.23% in a L/S ratio of 0.5 and 4.73% in a L/S ratio of 10. Iron leached 11.92% in a L/S ratio of 0.5 and 1.36% in a L/S ratio of 10. Manganese leached 6.74% in a L/S ratio of 0.5 and 0.84% in a L/S ratio of 10. Molybdenum leached 24.26% in a L/S ratio of 0.5 and BDL in a L/S ratio of 10. Nickel leached 13.51% in a L/S ratio of 0.5 and BDL in a L/S ratio of 10. Phosphorous leached 5.23% in a L/S ratio of 0.5 and BDL in a L/S ratio of 10. Lead leached 7.7% in a L/S ratio of 0.5 and 0.86% in a L/S ratio of 10. Uranium leached 29.97% in a L/S ratio of 0.5 and 2.84% in a L/S ratio of 10. Zinc leached 21.73% in a L/S ratio of 0.5 and 2.14% in a L/S ratio of 10. The other tailing samples (T2, T4) and the waste rock mix (C23) showed similar trends; however, the leaching percentage was generally lower than STP (See Chart 7).

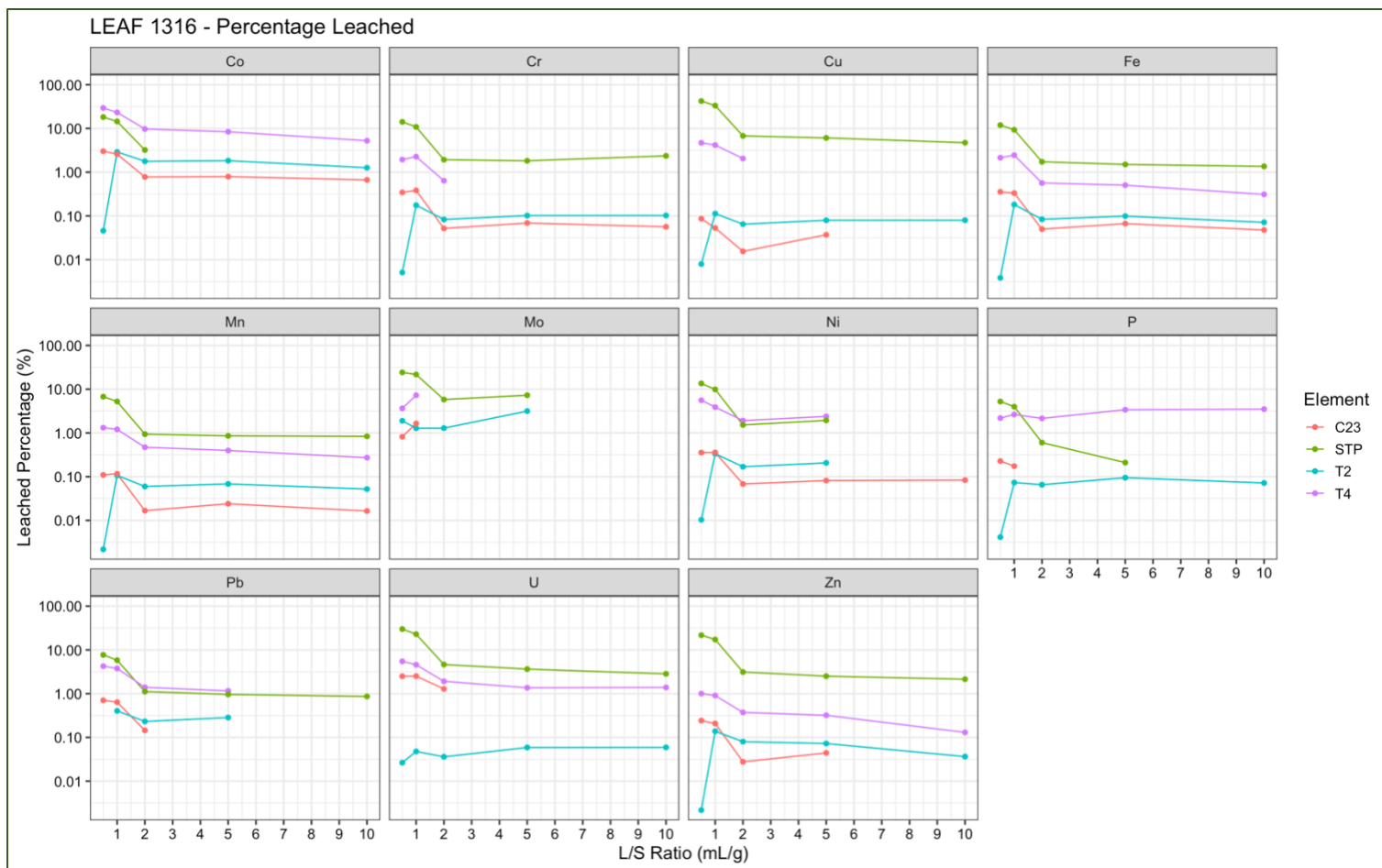


Chart 7 – Shows the percentage leached into solution from samples C23, STP, T2 and T4 during the LEAF 1316 experiment.

LEAF 1316 Leaching Concentrations

Lower liquid-to-solid ratios (less than 2) had the greatest effect on leachate concentrations due to less dilution. Aluminum effluents significantly exceeded the HBSL threshold in all samples at L/S ratios lower than 2. Beryllium exceeded the MCL at ratios lower than 2 in all effluents. Cadmium effluent extracted from STP exceeded the MCL at a ratio of 0.5, GLV at a ratio less than 1 and CCC at a ratio less than 2. Cobalt effluent from all samples crossed the HBSL threshold in all L/S conditions, although exceedance was much higher at lower ratios. Chromium effluent exceeded HBSL, GLV, CCC on all samples in L/S conditions lower than 4. Of particular

concern, STP and C23 surpassed the MCL threshold in L/S conditions under 1. Iron effluent exceeded CCC and GLV standards for all samples at ratios lower than 2. Lithium effluent exceeded HBSL standards for all samples in all conditions, although lower ratios had higher concentrations. Manganese effluent exceeded HBSL and GLV standards in all samples lower than 2. Molybdenum effluent extracted from STP exceeded HBSL standards at L/S ratios lower than 1. Nickel effluent exceeded CCC in ratios lower than 1 for all samples. All samples except for T2 were higher than the GLV at a L/S ratio of 0.5. Additionally, STP and C23 exceeded HBSL at a ratio of 0.5 and less than 1, respectively. Lead effluent extracted from all samples exceeded the MCL and GLV of lead at L/S ratios lower than 2. STP effluent exceeded the MCL by a large margin in ratios under 1. Antimony effluent extracted from T2 exceeded the MCL in the 0.5 L/S ratio condition. Thallium effluent exceeded MCL standards at ratios lower than 2 for T2, lower than 1 for T4 and STP and 0.5 for C23. Uranium effluents exceeded MCL and GLV standards from STP and T4 leachate in L/S ratios lower than 2, T2 leachate in conditions lower than 1 and C23 leachate in the 0.5 condition. Zinc effluent from all samples exceeded CCC in L/S conditions lower than 1, and STP effluent also exceeded the HBSL levels in these conditions (See Chart 8, 9 & 10).

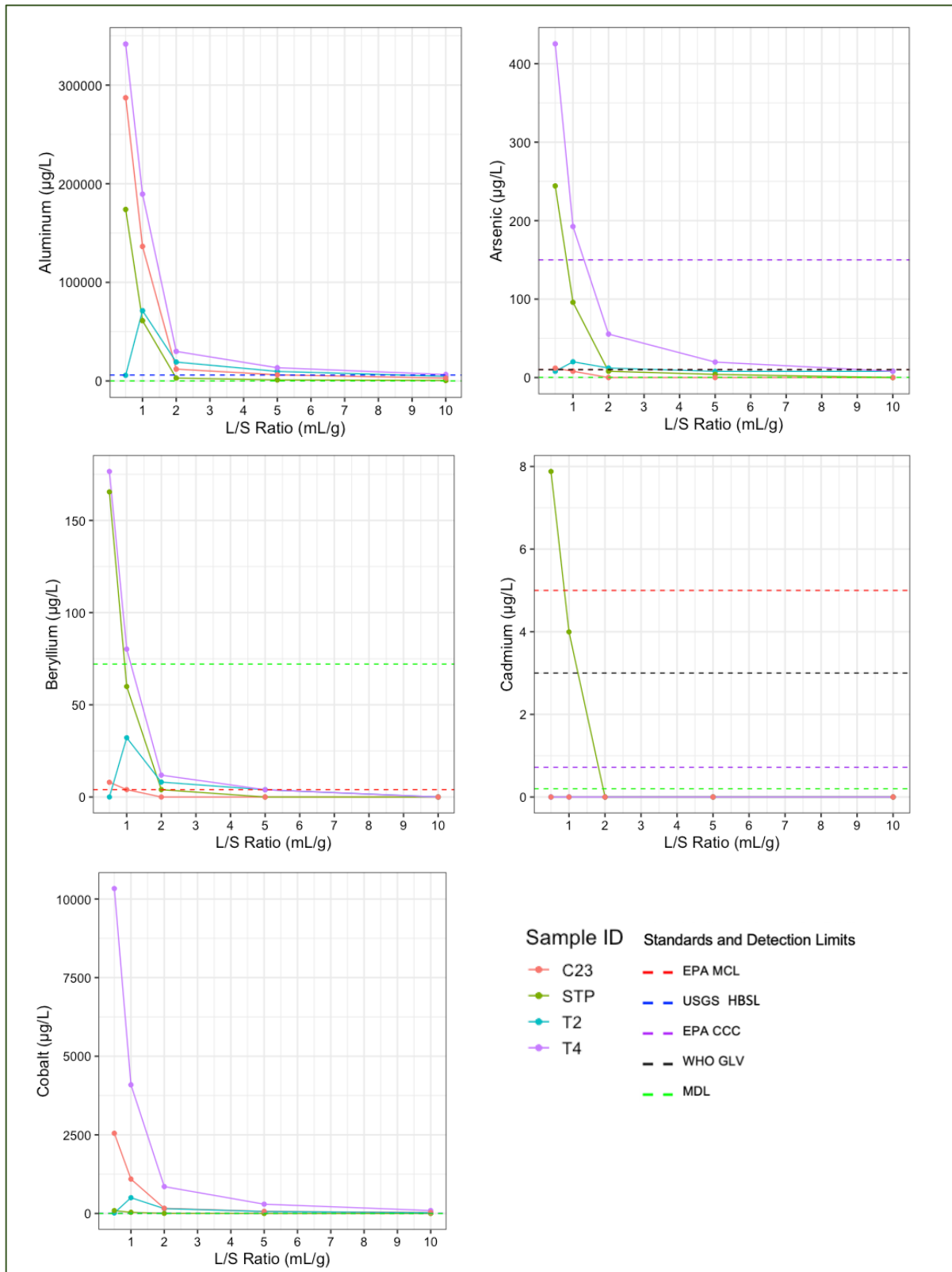


Chart 8 - LEAF 1316 results for aluminum, arsenic, beryllium, cadmium and cobalt. Leachate increased in lower ratio conditions. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

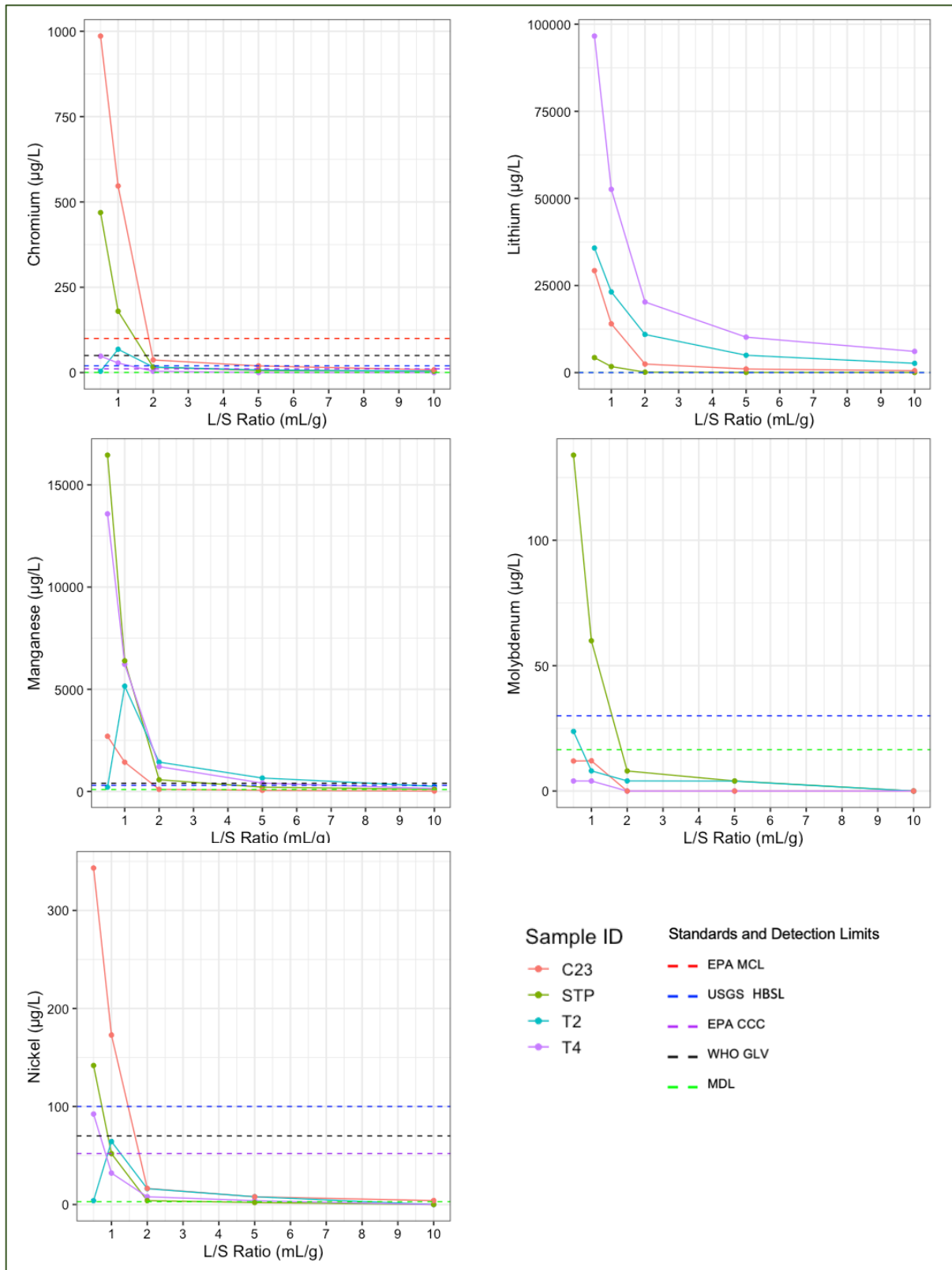


Chart 9 - LEAF 1316 results for chromium, lithium, manganese, molybdenum and nickel. Leachate increased in lower ratio conditions. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

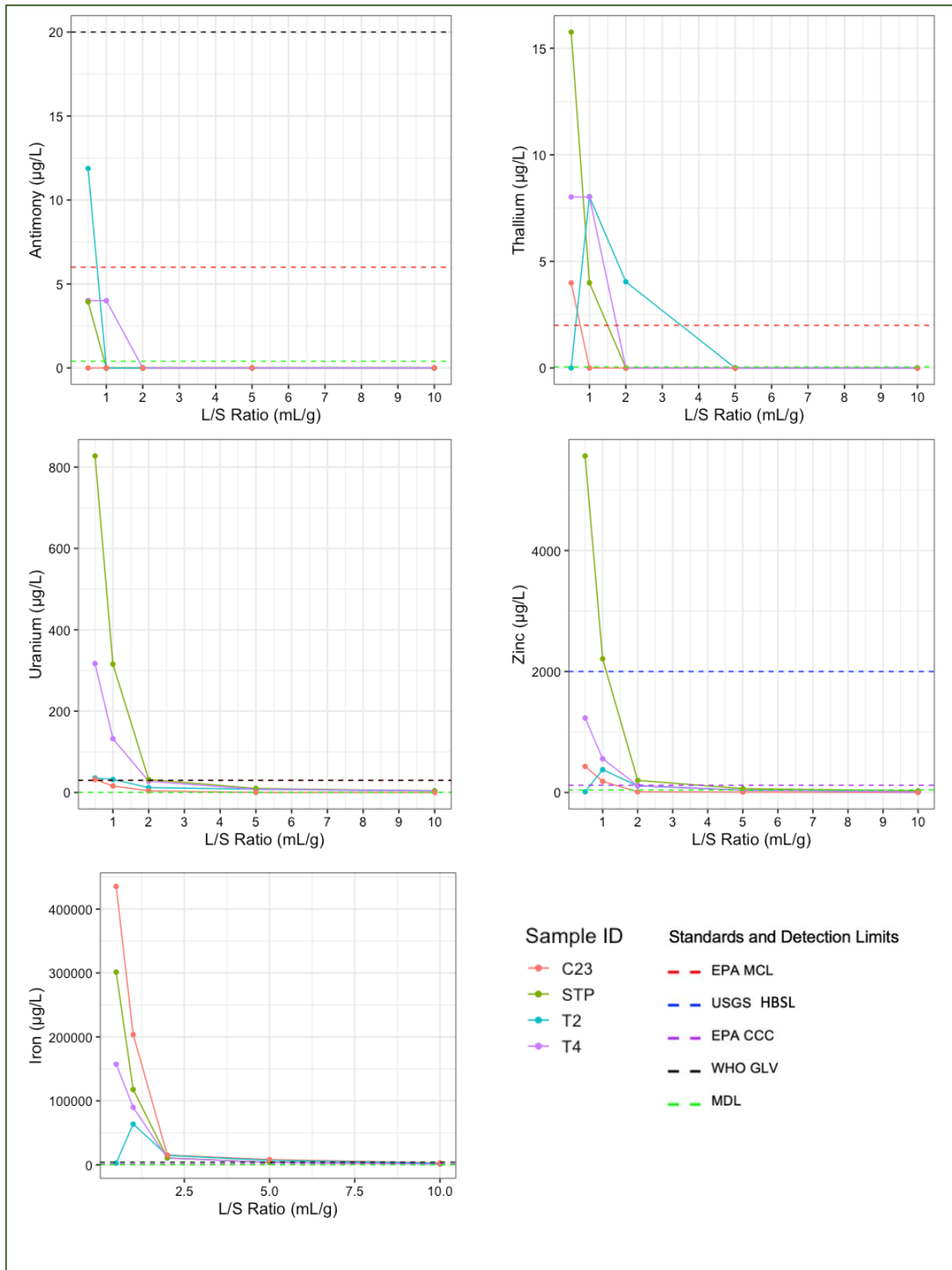


Chart 10 - LEAF 1316 results for antimony, thallium, uranium, zinc and iron. Leachate increased in lower ratio conditions. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

Coal and Lithium Mining LEAF Comparison to Enforceable EPA MCL Standard

Nine elements with MCL standards were measured between the coal ash and lithium data sets.

BRFA is a coal ash sample collected in Clinton, Tennessee from the TVA Bull Run Fossil Plant in a study that used both LEAF 1313 and 1316 to understand leachate possibilities.

LEAF 1313

Antimony effluent extracted from coal ash exceeded the MCL standard in all initial pH conditions except for the initial pH value of 2. All lithium mining samples were below the detection limit. Arsenic effluent from coal ash was consistently above the MCL at all initial pH values. Arsenic in the lithium mining tailing samples (T2, T4, STP) became highly mobilized in alkaline conditions greater than 10.5 with MCL exceedance occurring at initial pH values greater than 12. Further testing needs to confirm the results of arsenic in the lithium mining samples. Selenium effluent from coal ash was slightly exceeding or below the MCL threshold from highly acidic (pH 2) to moderately alkaline (pH 10.5) conditions. The coal ash mobilized to concentrations exceeding the MCL in alkaline conditions greater than 10.5. Lithium mining samples were consistently below the detection limit at all pH testing levels. Chromium effluent concentrations leaching from coal ash exceeded the MCL at all initial pH testing values. Lithium mining samples mobilized in more acidic (lower than pH 4) and alkaline conditions (greater than pH 10.5) but never exceeded the MCL. Thallium effluent concentrations leaching from coal ash exceeded the MCL at all concentrations except for the initial pH test value of 13. Mobilization increased with acidity and considerably exceeded the MCL at a pH value of 2. All lithium mining samples results were below the detection limit. Cadmium effluent concentrations for both coal ash and lithium mining samples were below the MCL except for coal ash at an initial pH

testing value of 2. Copper effluent concentrations did not surpass MCL thresholds for lithium mining and coal ash samples. Barium effluent concentrations did not surpass MCL thresholds for lithium mining and coal ash samples. Lead effluent was below the MCL limits for coal ash and lithium mining samples except for samples collected from the lithium mine STP where MCL limits were exceeded in both highly acidic (pH lower than 2) and basic (pH greater than 10.5) conditions. (See Chart 11 & 12 Below).

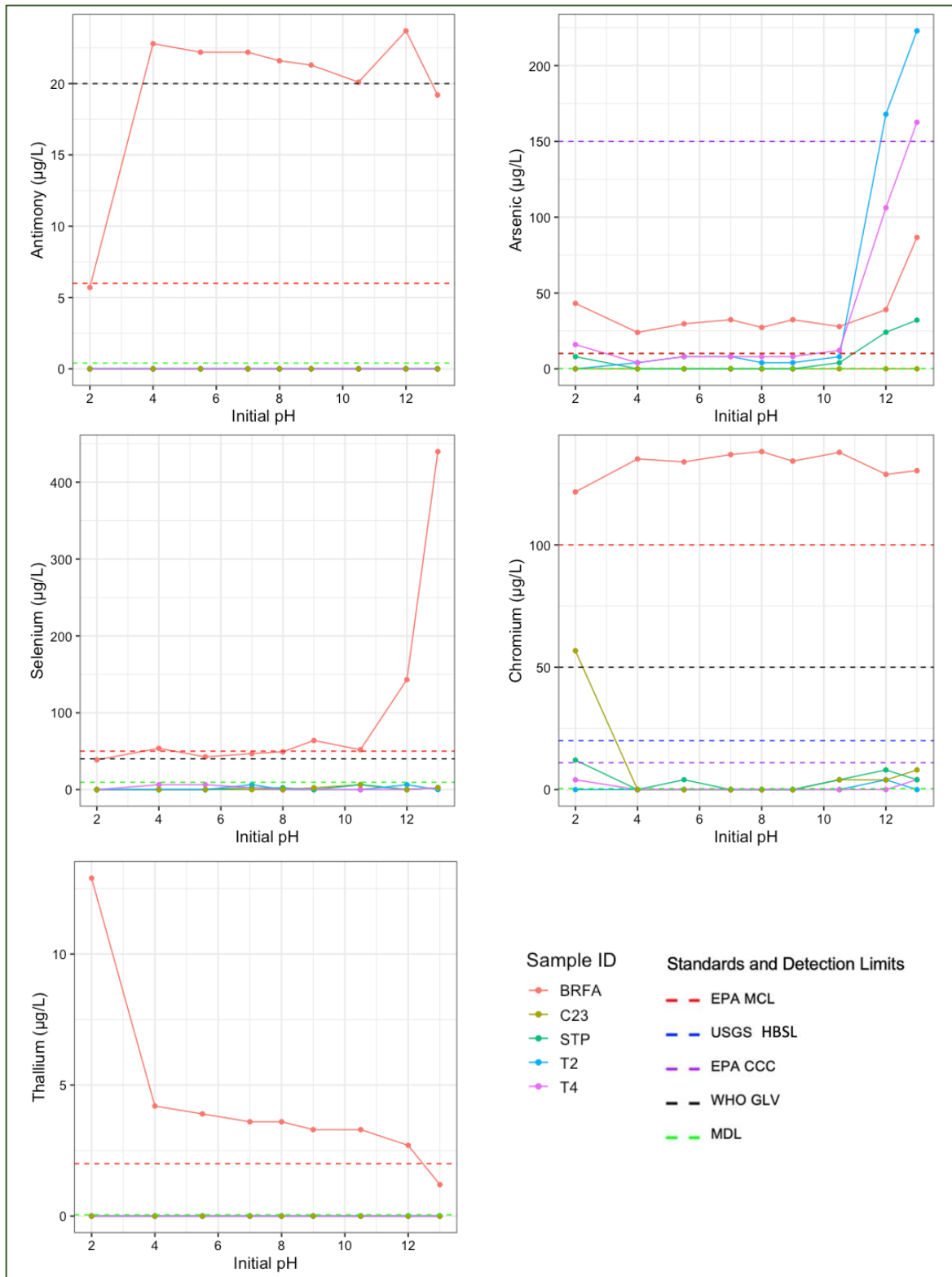


Chart 11 - A comparison of LEAF 1313 results from coal ash (BRFA) and lithium samples. Antimony, arsenic, thallium, selenium and chromium are plotted. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

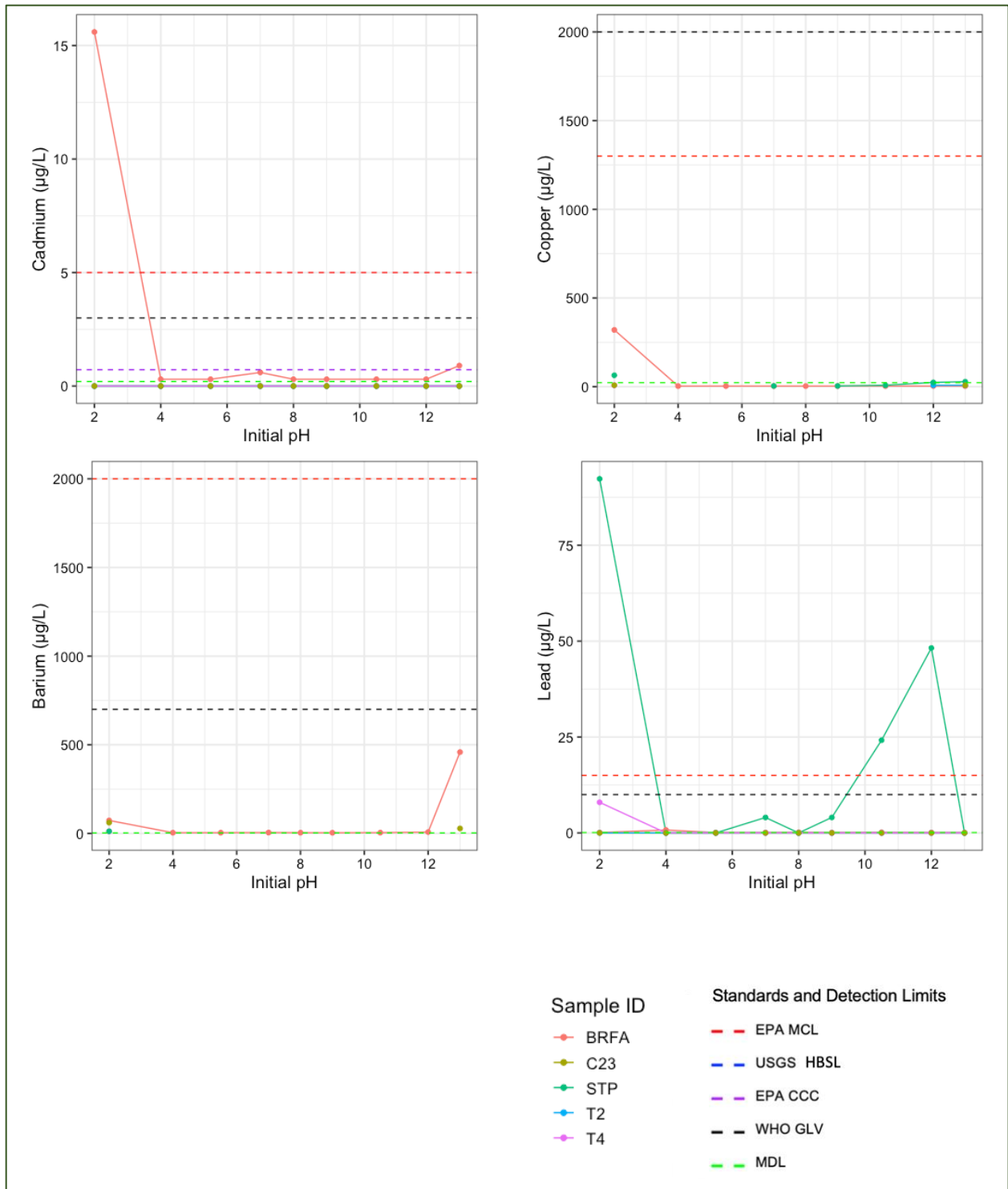


Chart 12 - A comparison of LEAF 1313 results from coal ash (BFRA) and lithium samples. Cadmium, copper, barium and lead are plotted. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

LEAF 1316

Copper effluent concentrations did not exceed MCL thresholds in coal ash and lithium mining samples across all liquid-to-solid ratios. Barium effluent concentrations did not exceed MCL thresholds in coal ash and lithium mining samples across all liquid-to-solid ratios. Antimony effluent from coal ash leachate had a measured concentration that exceeded MCL thresholds across all L/S ratios. Lithium mining samples did leach antimony at lower L/S conditions; T2 exceeded the MCL at the L/S ratio of 0.5. Dilution from higher L/S ratios produced results where the leachate was negligible. Chromium effluent concentrations from coal ash exceeded MCL standards in all L/S ratio conditions. Chromium was soluble in the lithium mining samples in lower L/S ratio conditions. C23 and STP in L/S ratios less than 1 produced effluent concentrations that exceeded the MCL. Selenium effluent concentrations from coal ash exceeded MCL standards in all L/S ratio conditions. Lithium mining samples hovered at or below the detection limit for all L/S ratio conditions. Thallium effluent concentrations were at or above MCL thresholds across all L/S ratios for coal ash. Thallium concentrations in the lithium mining samples were soluble, but effluent concentrations only exceeded the MCL thresholds in L/S ratio conditions less than 1 (T2, T4 & STP) and 0.5 (C23). Cadmium leachate concentrations exceeded the MCL threshold for both coal ash and the lithium mining sand tailings pile sample at lower L/S concentrations of 0.5 and less than 1, respectively. Lead leachate was soluble in the lithium mining samples. All lithium mining samples exceeded the MCL at lower L/S ratios (lower than 2). Coal ash was below the detection limit in all L/S ratio conditions.

Arsenic effluent concentrations of coal ash consistently exceeded the MCL threshold across all L/S ratio conditions. Lithium mining samples exceeded MCL thresholds at lower L/S ratios (lower than 2). T4 and STP were much higher than the MCL threshold in L/S conditions lower than 1. Arsenic results from the lithium mining samples need to be confirmed (See Charts 13 & 14).

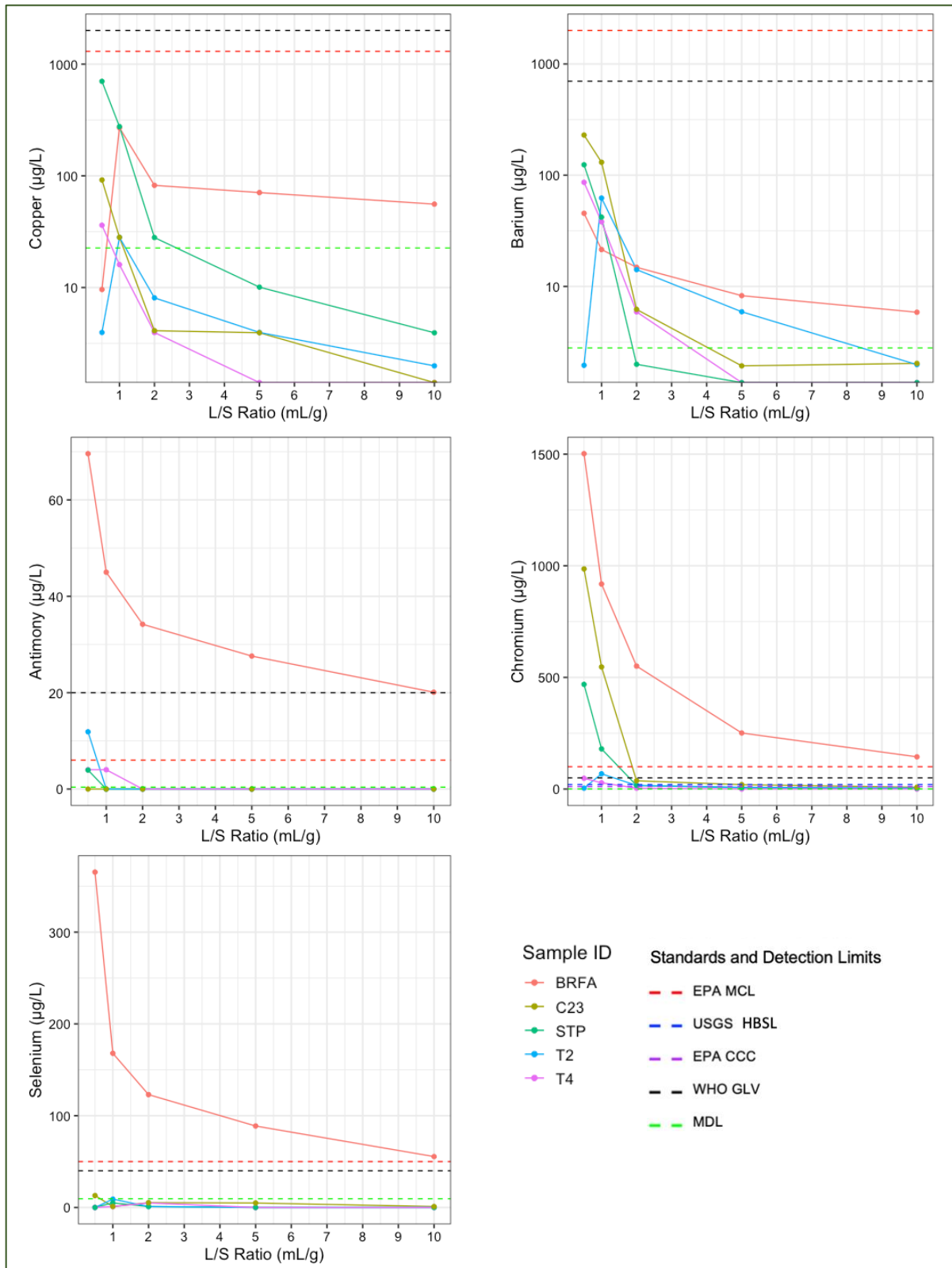


Chart 13 - A comparison of LEAF 1316 results from coal ash (BRFA) and lithium samples. Antimony, copper, barium, selenium and chromium are plotted. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

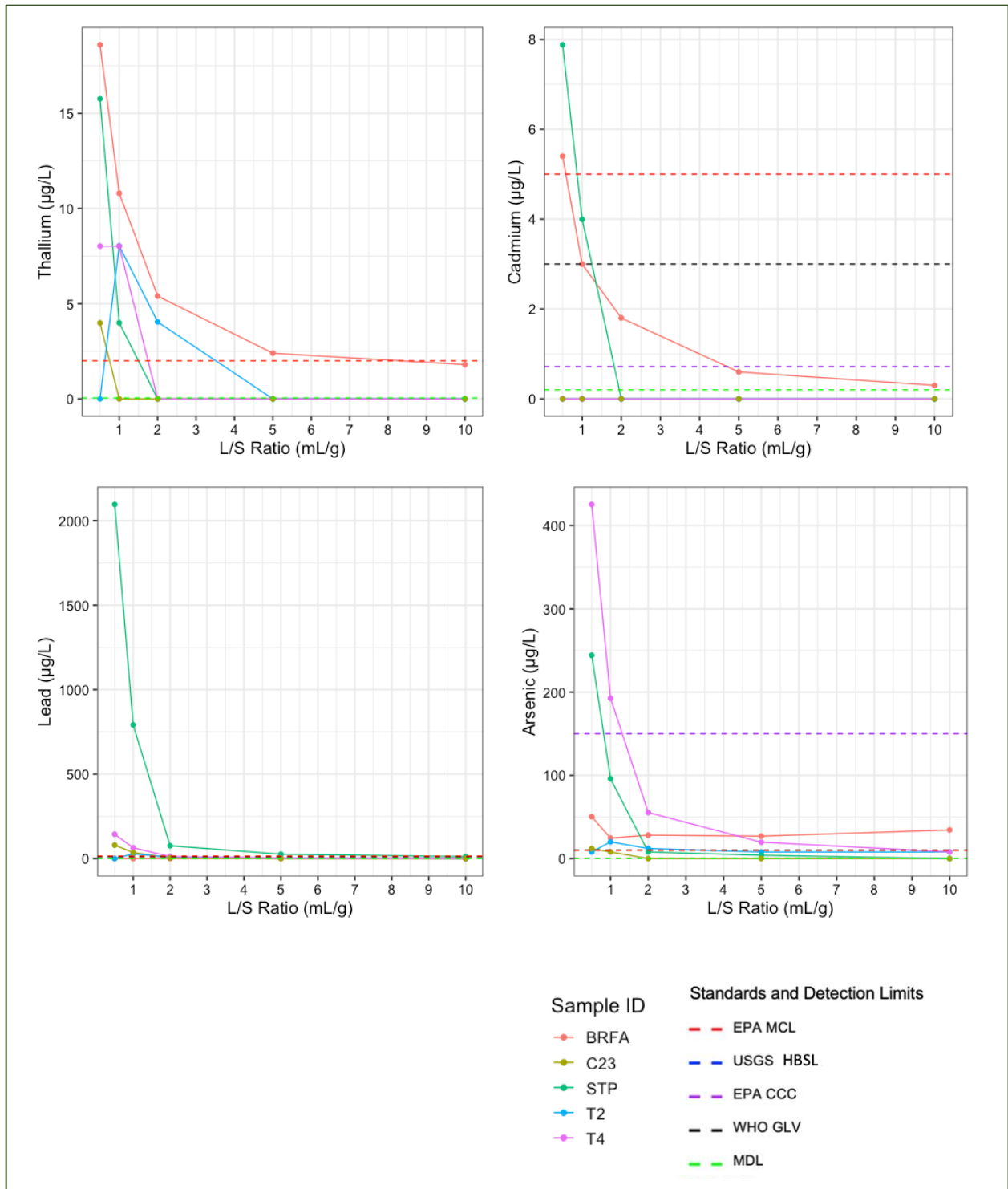


Chart 14 - A comparison of LEAF 1316 results from coal ash (BRFA) and lithium samples. Thallium, cadmium, lead and arsenic are plotted. Concentration values of 0 were below the detection limit. The constituent could be in the leachate in a trace amount. The EPA Maximum Contaminant Levels (MCL), EPA Criterion Continuous Concentration (CCC), World Health Organization Guideline Values (GLV) and the USGS's Health-Based Screening Levels (HBSL) are labeled where applicable.

The coal ash sample also turned deionized water alkaline with pH ranging between 9-10 in all L/S conditions (See Chart 15).

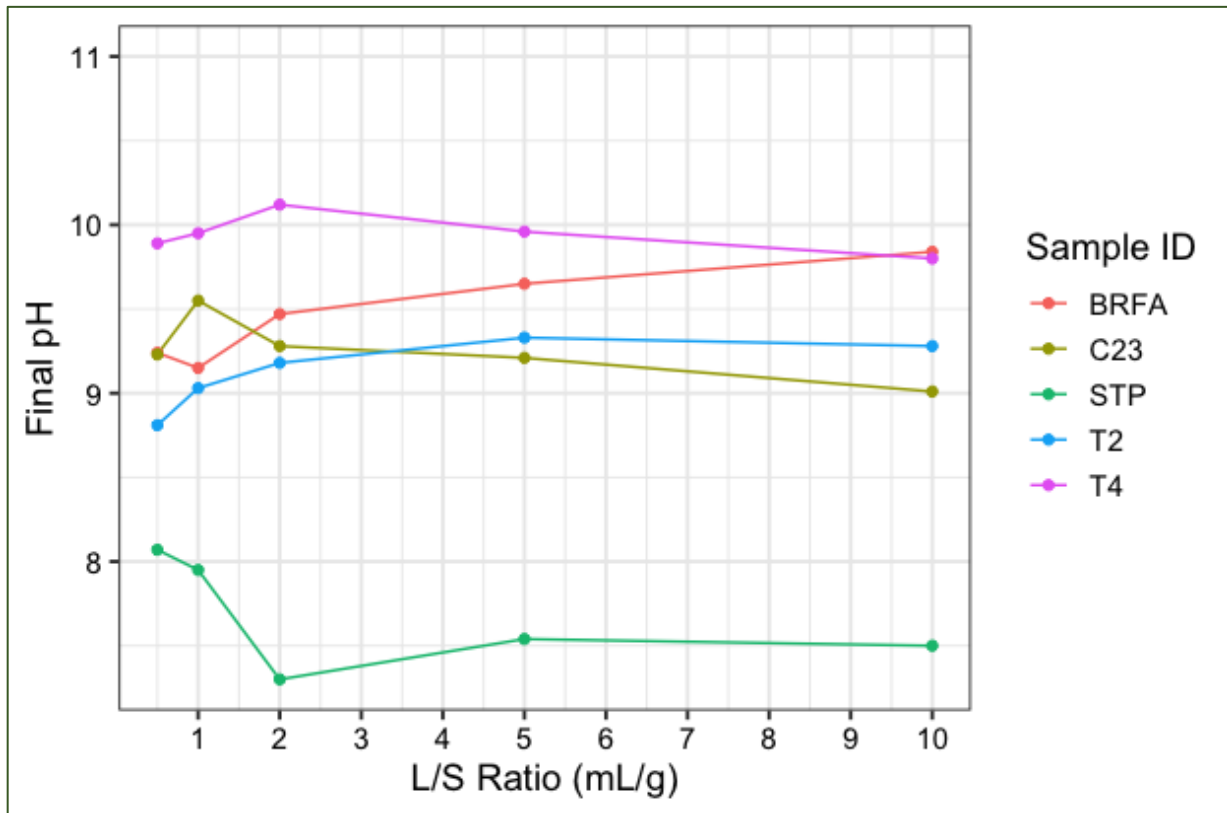


Chart 15 - Comparison of final pH values from LEAF 1316 tests of coal ash and lithium tailings.

Discussion

Significant Findings

The groundwater and surface water samples collected on-site had overall good water quality when compared to drinking water standards (EPA MCL, USGS HBSL, WHO GLV) and ecological standards (EPA CCC). The only measurable concerns were with zinc and lithium (See Table 2 & 3). Lithium exceeded an unenforceable USGS health advisory drinking water standard, i.e., HBSL, of 10 µg/L, with the highest concentration of the two samples of 46,764

$\mu\text{g/L}$ in the groundwater. The USGS also has a second drinking-water-only standard set at 60 $\mu\text{g/L}$ (Lithium in U.S. Groundwater, 2021). The two samples on-site exceeded this USGS standard as well. Zinc exceeded an unenforceable ecological standard of 120 $\mu\text{g/L}$ in the groundwater sample at 166 $\mu\text{g/L}$. While data of reference water resources were not collected in this study, it seems that the legacy lithium mining inherently has altered the surface area of the residual rocks and enhances its exposure to water. These changes can potentially promote chemical reactions through increased water-rock interactions (Holdren & Speyer, 1985), resulting in higher lithium and zinc concentrations. Both the groundwater sample and surface water sample collected on-site were alkaline with a pH of 9.34 and 8.39, respectively. The observed water conditions on-site in these two samples suggest that residual rock at the mine site will produce effluent with higher alkalinity.

The objective of the bulk characterization experiment was to understand how water quality can potentially change from exposure to meteoric water and mobilization of toxic elements from the residual rocks to the associated water resources. The bulk characterization, i.e., total concentration of elements in the rocks, highlighted that the chemical composition of a hard rock lithium site is complex (See Chart 1 and Table 4). Bulk chemical concentrations of samples C23, T2, T4 and STP all had a lower enrichment factor of arsenic (0.03-0.23), barium (<0.01-0.1), lead (0.1-0.8) and antimony (0.07-0.6) relative to the upper continental crust averages reported by Rudnick and Gao (2014). The tailings solid samples (STP, T2, T4) had a relative high enrichment factor of beryllium (between 8-53) and thallium (between 1-8) to the upper continental crust. Waste rock (C23) had a lower enrichment factor of beryllium and thallium that was approximately 0.55 for both constituents relative to the upper continental crust. An opposite

pattern was observed with chromium and copper where waste rock (C23) had a higher enrichment factor relative to the upper continental crust between 1.5-2, and all tailings (STP, T2, T4) had an enrichment factor less than 1. Uranium had an enrichment factor greater than the upper continental crust for T2 at approximately 25, about the same for T4 at 1.07 and lower for STP and C23 ranging between 0.2 and 0.5. An interesting observation from this result is the enrichment of uranium in T2, which is tailings derived through magnetic separation. The enrichment factor of cadmium and selenium were mixed. Cadmium had higher enrichment factors greater than the upper continental crust for T2 (9.96) and C23 (2.61) with lower enrichment factors for STP (<0.01) and T4 (0.61). Enrichment factors of selenium were greater than the upper continental crust in samples T2, STP and C23 ranging between approximately 2-4 and lower for T4 at 0.31. Assumptions on water quality impacts from the observed patterns in this comparison cannot be made. The takeaway is that there are potential contaminants present in the minerology considered hazardous for human consumption and ecosystems (National Primary, 2023). The comparison to the study by Rudnick and Gao (2014) shows that there are samples with bulk concentrations of beryllium, thallium, chromium, copper, uranium, cadmium and selenium that are higher than the average concentrations observed in the upper continental crust.

The first measurement taken after completing LEAF 1313 and 1316 tests was pH. Both tests indicated that leachate from the waste rock from mining lithium in a pegmatite source produces alkaline waters (Chart 2 & 6). The final pH samples from LEAF 1316 that used deionized water across all samples and L/S ratios ranged between 7.3-10.12. These results are consistent with the measured pH of surface water (8.39) and groundwater (9.34) collected on-site (See Table 2 & 3). Additionally, these results are consistent with a previous study by Rahn et al. (1996) that studied

alkalinity associated with a pegmatite source in the Black Hills of South Dakota and found pH values ranging between 8-9. Leachate results from the pegmatite at the Whabouchi lithium mine in Quebec, Canada had results that were less alkaline with leachate ranging between 6.5-8.5 (Roy et al., 2020). These results do not align with the acidic pH values ranging from 4.8-6.4 measured in surface water and groundwater samples taken around a pegmatite lithium mine site in Portugal (Rodrigues et al., 2019). It should be noted that the study in Portugal did not directly measure pegmatite leachate. The low to moderate alkaline conditions observed in this study could be favorable for water quality as it would not generate acid mine effluents. Alkaline conditions can promote mobilization and solubility of some oxyanion-forming elements such as uranium that can potentially affect the water quality. In the lab setting, less mobilization of contaminants of concern in the lithium residual waste rock occurred within the observed buffering capacity of pH 6-10 for initial pH conditions ranging from 4-10.5. Highly alkaline conditions resulted in increased mobility of contaminants. Overall, the alkaline conditions induced from water-lithium ore interactions suggests that there is a low likelihood of the formation of acidic effluents. Therefore, the hazard of acid rock drainage that commonly occurs from mining of coal and other types of ores extracted for critical raw materials is unlikely to occur near a pegmatite lithium mine site in North Carolina.

The LEAF experiments were used as a methodology to understand the potential risks associated with the constituents observed in the waste rocks from the bulk characterization. Percentage mobilized from the bulk sample was calculated by dividing LEAF test concentrations by bulk characterization concentrations (normalized to the mass of solid used in the experiment, in mg/kg). LEAF 1316 used L/S ratios to simulate permeability and porosity of a field environment.

Lower L/S ratios are designed to reflect a low-porous and low-permeable environment. In the low L/S conditions, a higher percentage of leached elements occurred. This trend was observed in all samples: C23, STP, T2 and T4. The effect of low L/S conditions was most pronounced in sample STP. Looking primarily at constituents with enforceable drinking water standards, a high percentage of chromium (14.12%), copper (42.23%), lead (7.7%) and uranium (29.97%) were mobilized in L/S 0.5 conditions for sample STP. The importance of higher porosity and permeability can be seen from the results of sample STP in L/S 10 conditions given that a lower percentage of chromium (2.36%), copper (4.73%), lead (0.86%) and uranium (2.84%) were mobilized. These results indicate that intense water to rock interactions under low L/S can promote the mobilization of these elements (See Chart 7). Alkaline conditions in the effluents generated in the in LEAF 1313 resulted in a higher percentage of uranium leaching (60.9% in pH 13) than observed in LEAF 1316 (See Chart 3). Environmental managers need to be aware that chromium, copper, lead and uranium could potentially leach out from pegmatite in areas of hard rock lithium mining.

There were constituents without enforceable water quality standards that mobilized in the LEAF tests as well. Although acidic conditions are unlikely at a lithium pegmatite mine site in North Carolina, lab conditions utilizing a pH solution of 2 in LEAF 1313 resulted in a higher percentage of calcium (STP leached 36.83%), cobalt (T4 leached 100.68%), cesium (C23 leached 17.34%), manganese (T4 leached 28%), strontium (T4 leached 14.45%) and zinc (STP leached 38.66%) leaching. Additionally, phosphorous was mobile in the acidic condition pH 2 with T4 leaching 26.73% and alkaline condition pH 13 with STP leaching 12.91%. In LEAF 1316, the lower L/S conditions with intense water to rock interactions resulted in increased

mobilization of some contaminants with unenforceable water quality standards. Once again, the trends were similar but most pronounced in STP. STP in L/S condition 0.5 leached a high percentage of cobalt (18.19%), iron (11.92), manganese (6.74%), molybdenum (24.26%), nickel (13.51%), phosphorous (5.23%) and zinc (21.73%). Although these constituents do not have enforceable drinking water standards, environmental managers should be aware of the conditions that these constituents became readily available.

A high percentage does not need to be leached for a constituent to become a water quality issue. If a constituent is abundant in the aquifer rock/solid, a small percentage leached can make a significant difference to water quality. Additionally, some elements are toxic and only a small percentage of mobilization would negatively affect the associated water quality. For example, the abundance of aluminum in the pegmatite resulted in the highest leachate result of 341,602 µg/L in L/S conditions of 0.5 for sample T4, which surpassed the USGS HBSL of 6,000 µg/L, despite leaching only 0.13% of the total concentration observed in the bulk characterization (See Chart 4 & 8). Beryllium also leached a low percentage in comparison to the bulk characterization. The highest percentage of beryllium leached between the two LEAF tests was 3.49%, from waste rock sample C23 in a pH condition of 2. Despite the low percentage mobilized, there were conditions observed in the lab where the concentrations showed high concentrations in the leachates. This is because only 4 µg/L is needed to exceed the enforceable MCL threshold; a very small concentration of beryllium in drinking water can have adverse health effects (National Primary, 2023). The comparison to multiple water standards set by US government agencies and the World Health Organization highlights the potential environmental effects of the leachates generate from lithium hard rock mining.

Results from the LEAF 1313 and 1316 methodologies indicated that there were certain experimental conditions (acidity and water-rock interactions) where constituent concentrations in leachates extracted of waste rock and tailings from a lithium mine site of a pegmatite source in North Carolina exceeded ecological and drinking water quality standards. Beryllium exceeded drinking water (MCL) standards under acidic and low L/S conditions. Cobalt exceeded drinking water (USGS HBSL) standards under acidic and low L/S conditions. Lead exceeded drinking water (MCL & GLV) standards under acidic and alkaline conditions. Iron exceeded ecological (CCC) drinking water (GLV) standards under acidic and alkaline conditions. Manganese exceeded drinking water (HBSL & GLV) standards under acidic and most L/S conditions. Nickel exceeded ecological (CCC) and drinking water (HBSL & GLV) standards under acidic and low L/S conditions. Aluminum exceeded drinking water (HBSL) standards under acidic, alkaline and all L/S conditions. Chromium exceeded ecological (CCC) and drinking water (GLV, HBSL & MCL) standards under acidic, alkaline and low L/S conditions. Lithium exceeded drinking water (HBSL) standards under acidic, neutral, alkaline and all L/S conditions. Uranium exceeded drinking water (MCL & GLV) standards under acidic, alkaline and low L/S conditions. Zinc exceeded ecological water (CCC) standards under acidic and low L/S conditions. Cadmium exceeded ecological (CCC) and drinking water (MCL & GLV) standards under low L/S conditions. Molybdenum drinking water (HBSL) standards under low L/S conditions. Antimony and thallium exceeded drinking water (MCL) standards under low L/S conditions. The potential for water contamination exists with mining of pegmatite as observed in the laboratory setting (See Table 3). Field conditions need to be understood to determine the level of actual risk associated with water contamination.

Highest Elemental Concentrations in LEAF Tests Compared to EPA MCL						
Element	Sample	LEAF Test	Condition	MCL (ppb)	Highest Measured Sample Concentration (ppb)	Sample Concentration to MCL Ratio
Lead	STP	1316	L/S 0.5	15	2096	139.73
Beryllium	T4	1316	L/S 0.5	4	177	44.25
Uranium	STP	1316	L/S 0.5	30	827	27.57
Chromium	C23	1316	L/S 0.5	100	986	9.86
Thallium	STP	1316	L/S 0.5	2	16	8.00
Antimony	T2	1316	L/S 0.5	6	12	2.00
Cadmium	STP	1316	L/S 0.5	5	8	1.60

Table 5 - The highest measured concentrations from both LEAF tests are compared to EPA MCL water quality standards. The results suggests that low L/S conditions can have a significantly negative impact on water quality.

An environmental impact study (EIS) at the Barroso Mine in Portugal stated that the fragmentation of pegmatite from mining can result in the release of previously immobilized elements into the water. The EIS study did not clearly state what constituents may mobilize, although it provided constituents that will be measured and monitored (Chaves et al., 2021; Visa Consultores, 2018). Results from LEAF testing in this study indicate that the exposure of the pegmatite to highly alkaline and acidic conditions as well as water under low liquid-to-solid ratios would increase the mobility of some constituents and have an impact on the quality of the associated water resources, although the actual impact may vary and would be dependent on field conditions. High levels of manganese and lead have been reported in the surface water at the Jiajika lithium mine site in China (Juanqin et al., 2021). The LEAF tests found that manganese and lead can be mobilized from pegmatite in relatively elevated concentrations under certain L/S and pH conditions. However, the results of the LEAF tests are not consistent with the results reported by Rodrigues et al. (2019) in Portugal and the modeling effort by Yu & Yu (2019) that concluded lithium mining activity from a pegmatite source will not alter the water quality of the surrounding area.

The transition to a clean grid and transportation system requires raw materials. Currently lithium is one of the critical minerals used in substantial amounts to support energy storage. Part of this transition to a clean and sustainable grid requires moving away from coal given that the combustion of coal releases the greenhouse gas carbon dioxide into the atmosphere. Also, the residual coal waste, also known as coal ash, is proven to negatively impact water quality if not properly managed. This study uses the LEAF methodology to compare the water quality of effluents extracted from lithium mining compared to those of coal ash. The comparison aims to show how changes in residual waste materials from coal ash to residual lithium mining rocks during the current energy transition can potentially impact the quality of associated water resources. There are multiple drinking and ecological standards that can be compared. The EPA MCL was selected for analysis since this is an enforceable standard in the United States where the established limits are deemed critical to human health.

The LEAF 1313 comparison indicated that pH influences the leachate in both lithium sources and coal ash. Results from the alkaline conditions are of particular interest because both the lithium mine residual rocks and coal ash produce alkaline effluents upon interaction with water (See Chart 15). Although effluents of lithium mine residual rock and coal ash generate alkaline effluents, the concentrations of trace elements in the lithium mine residual rock effluents are overall systematically lower than those of coal ash effluents (See Table 6). Coal ash leaching at moderately alkaline pH conditions would induce high levels of antimony, arsenic, selenium, chromium, and thallium. In contrast, effluents derived from leaching of lithium tailings would likely have much lower concentrations (See Table 6).

LEAF 1313 Comparison of Lithium Tailings and Coal Ash to EPA MCL									
Initial pH	Element	MCL	Concentrations (ppb)				Coal Ash to STP Ratio	Coal Ash to T2 Ratio	Coal Ash to T4 Ratio
			Lithium Mining (STP)	Lithium Mining (T2)	Lithium Mining (T4)	Coal Ash			
7	Antimony	6	1	1	1	20	20.0	20.0	20.0
9	Antimony	6	1	1	1	19	19.0	19.0	19.0
7	Arsenic	10	1	8	8	28	28.0	3.5	3.5
9	Arsenic	10	1	4	8	87	87.0	21.6	10.9
7	Chromium	100	1	1	1	138	138.0	138.0	138.0
9	Chromium	100	1	1	1	130	130.0	130.0	130.0
7	Selenium	50	2	7	2	52	21.7	3.1	26.0
9	Selenium	50	1	1	1	440	440.0	440.0	440.0
7	Thallium	2	1	1	1	3	3.0	3.0	3.0
9	Thallium	2	1	1	1	1	1.0	1.0	1.0

Table 6 - Comparison of leachate between lithium tailings and coal ash constituents with established EPA MCL thresholds. Leachate in pH 7 is used to compare coal ash effluent and lithium tailings effluent in neutral water. Leachate in slightly alkaline conditions (pH 9) is compared given coal ash and lithium tailings both produce alkaline water. Numbers in red were below detection and a value of 1 was used to assist interpretation of ratio multipliers. Yellow highlighted cells indicated exceedance of MCL threshold.

The comparison of coal ash and lithium residual rock using LEAF 1316 provided additional insights on how water quality could be affected. Coal ash and lithium residual rock similarly had higher levels of contaminants in leachates generated under low L/S ratio conditions. Under low L/S ratios, the effluents from lithium residual rock contained relatively high concentrations of contaminants, in some cases even higher than those in coal ash effluents under similar low L/S ratios (Table 7). Therefore, intensive water-rock interactions under low porosity of the aquifer rocks could potentially induce contamination of the ambient water. In particular, elevated levels of arsenic, lead, cadmium, thallium, antimony and chromium were detected in lithium residual rock effluents under low L/S ratio experiments (See Table 7).

LEAF 1316 Comparison of Lithium Tailings and Coal Ash to EPA MCL									
Ratio	Element	MCL	Concentrations (ppb)				Coal Ash to STP Ratio	Coal Ash to T2 Ratio	Coal Ash to T4 Ratio
			Lithium Mining (STP)	Lithium Mining (T2)	Lithium Mining (T4)	Coal Ash			
0.5	Antimony	6	4	12	4	70	17.7	1.5	17.3
5	Antimony	6	1	1	1	28	27.6	27.6	27.6
0.5	Arsenic	10	244	8	425	50	0.2	0.0	0.1
5	Arsenic	10	4	8	20	27	6.7	0.8	1.4
0.5	Cadmium	5	8	1	1	5	0.7	0.7	5.4
5	Cadmium	5	1	1	1	1	0.6	0.6	0.6
0.5	Chromium	100	469	4	48	1502	3.2	0.8	31.2
5	Chromium	100	6	8	1	251	41.4	5.2	251.1
0.5	Lead	15	2096	1	144	1	0.0	0.0	0.0
5	Lead	15	26	4	4	1	0.0	0.0	0.3
0.5	Selenium	50	1	1	1	365	365.4	365.4	365.4
5	Selenium	50	1	1	1	89	88.8	88.8	88.8
0.5	Thallium	2	16	1	8	19	1.2	1.2	2.3
5	Thallium	2	1	1	1	2	2.4	2.4	2.4

Table 7 - Comparison of leachate between lithium tailings and coal ash constituents with established EPA MCL thresholds. Ratio of 0.5 reflects leachate in low-porous environment and ratio of 5 reflects moderately porous environment. Numbers in red were below detection and a value of 1 was used to assist interpretation of ratio multipliers. Yellow highlighted cells indicated exceedance of MCL threshold.

Limitations

Results from this study provide information on how acidity and liquid-to-solid ratios would affect the solubility of inorganic elements into associated water resources. Although these factors are significant in determining how contaminants may leach in field conditions, there might be other factors. One example of a factor not accounted for in this study that can potentially influence leaching of oxyanion elements is redox reactions. For example, the speciation, solubility and partitioning of constituents like chromium, arsenic and uranium are affected by redox conditions (Kosson et al., 2019). Another example is the presence of organic matter that can increase solubility of a constituent through ion exchange (Kosson et al., 2019). A full understanding of leachate potential in real field conditions would need to also include these factors.

Application of LEAF Results

LEAF data that reflects L/S ratios and pH levels of actual field conditions can be incorporated into site-specific models. Incorporation of LEAF results into site-specific models like a fate and transport model would be a proper next step at a mine site. This type of modeling forms a more comprehensive evaluation of how contaminants move and interact throughout a mine site (Kosson et al., 2019). The leachate characterization that is derived from LEAF results alongside site-specific models, which account for variables like topography and hydrology patterns, can help environmental managers determine how to design storage and safely manage waste rock on-site (Office of Wastewater Management, n.d.). There are many different management or remediation paths that can be taken dependent on the site. Data from LEAF provides the initial information needed to determine best waste rock and tailings management practices.

Conclusion

The LEAF 1313 and 1316 methodologies provide an initial understanding of how lithium mining from a pegmatite rock source can alter water quality by testing varying pH and liquid-to-solid conditions. The existing literature at lithium pegmatite sites has inconclusive findings on how water quality may be impacted. This study provides new and valuable insights as the LEAF tests indicate that residual rock waste from a pegmatite lithium mine in North Carolina produce alkaline effluent. This finding is supported from the alkaline conditions observed from the two samples collected on-site, i.e., one groundwater sample and one surface water sample. The moderately alkaline conditions observed in the water samples collected on-site and lithium residual rock effluents produced in the laboratory setting suggest that the potential issue of acid rock drainage arising from the mining of pegmatite in this region is improbable. Additionally, the

laboratory results of the LEAF tests suggests that a lithium mining operation in North Carolina with moderately alkaline effluent has better water quality than a coal ash pond, which provides insight on how industrial effluents may change should the current energy transition continue. Environmental managers should utilize the buffer capacity of the residual waste rock that kept the final pH between 6-10 for initial conditions ranging 4-10.5. In the laboratory setting, the buffer capacity prevented some potential contaminants from mobilizing, e.g., uranium mobilized in highly alkaline conditions greater than pH 10.5. How contaminants may mobilize in the field setting cannot be directly inferred from this study. Additional modeling and data collection on-site is needed. However, an environmental manager at a pegmatite lithium site in North Carolina should be aware of how constituents mobilized in the LEAF experiments as certain lab conditions promoted leaching of contaminants of concern, including chromium, lead, uranium, beryllium, cadmium, antimony and thallium. Results observed in this study can serve as a reference when designing water resource monitoring and management plans that ensure healthy drinking and ecological water quality throughout the life of the mine.

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