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Dispersion modelling and leachability of heavy metals from tailings dam material of a gold cyanidation plant in Zimbabwe

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ABSTRACT

Notable pollution impacts on tailings dams and surrounding areas at gold mines have been a major concern in Zimbabwe. This study investigated the major environmental pollutants propagating from tailings dams in gold operations. Soil and water samples were collected from a gold mine's active slimes dam and its surroundings. The samples were analysed for physico-chemical parameters and 13 elements which included; lead, chromium, iron, manganese, nickel, copper, arsenic, cobalt, cadmium, mercury, sodium, cyanide and sulphide. Atomic Absorption Spectroscopy (Varian Spectra AA 200 model) was used in the chemical analysis of heavy metals. In order to determine the relationship between parameters in the tailings dam and seepage (SP) water, a correlation matrix and a panel of regression equations were formulated. Single batch, 24-hour column leach tests were done on the tailings dam soil to ascertain the dissolution and mobility rate of the heavy metals, manganese, arsenic, iron, chromium and lead, under varying pH conditions. Highly positive correlations (> 0.90) were observed between the following pairs; Mn(SP) and Fe (0.99), Mn(SP) and Ammonia (0.96), Mn(SP) and Na (0.92), Fe(SP) and Fe(0.975), Fe(SP) and Ammonia (0.93), Ni(SP) and Fe (0.908), and Ni(SP) and Na (0.92). Relatively weak correlations (<0.50) were found between the following variables: Sulphate(SP) and TDS (0.293), TDS(SP) and Na (0.248), TDS(SP) and Ammonia (0.382), and TDS(SP) and TDS (0.316). The results also showed that heavy metals; manganese, iron and nickel in the see-page water stream have a high correlation value (> 0.80). The findings indicate that theseheavy metals are being released from a common source; dissolution of sulphide minerals within the tailings dam soil.Manganese had the highest extraction rate across the pH range investigated, having a maximum of 5.8% extraction at pH 3.It was concluded that a pH range of 6 to 9 proved to be the optimum in minimizing the heavy metals solubility.

Key words: Pollution, tailings, heavy metals, leach, pH

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1. INTRODUCTION

Environmental Conscious Manufacturing (ECM) requires that industrial players must strive to maintain the natural state of the environment. This research seeks to explore ways of minimizing environmental impacts of tailings dams in gold operations utilising the cyanidation route. Gold extraction using cyanidation involves the use of chemical reagents to dissolve the gold minerals into solution. However, the dissolution process is not selective, resulting in other elements dissolving together with the gold. The solution and ground solid ore mixture, after separating the gold, is then discarded to the tailings dam. On setting up a tailings impoundment, there is an upset of the natural ecosystem since there is ground excavation on a vast area. Pollutants from mine operations result in costly environmental and socio-economic impacts. It is common practice for most operations to re-vegetate the slimes dam areas in an effort to minimise effects such as dust and pollution of water streams. There have been attempts to try and vegetate active tailings dams at most gold mines with little success. Tailings dams cause a lot of environmental pollution in terms of Acid Mine Drainage (AMD), Heavy Metals and Cyanide Species contamination of the soils, surface and ground water. Lack of vegetation would also aid to air pollution as dust would be generated from the walls of the dam.

2. BACKGROUND

The study area is a gold mine that is situated in the greenstone belt of Bulawayo in Zimbabwe.It comprises a single underground operation, where ore is processed at a central processing facility, using a combination of conventional milling and a carbon-in-pulp process.The processing plant current milling capacity is 33000 tonne per month of ore at an average mined grade of approximately 5g/tonne.The gold mine is situated in the Bulawayo. The ore deposits show significant hydrothermal alteration that is frequently associated with sulphide mineralization. Strong carbonation, silification and in extreme cases propylitisation occur together with sulphides. There are four decommissioned tailings dumps at the mine. The current active tailings dump is located in a natural hollow closed off on two sides of hills (valley). The dam wall was initially constructed using soil which was piled up to form an embankment. Six-inch PVC pipes were laid under the dam wall to allow for see-page as the water sips downwards through the soil. On deposition of the tailings in the tailings dam, separation occurs between the finely ground rock and the water. The tailings are made up of about

38% solids and the rest being water.

After the extraction of gold, there is need to dispose the tailings residue in an environmentally friendly way. Tailings from gold cyanidation plants contain cyanide and heavy metal ion species which have serious environmental risks because of their highly toxic nature (Keskinen 2013). According to Acheampong & Lens (2011), many industrial players discharge their effluents without sufficient characterization, quantification and treatment, because of limited economic and technological resources. The same authors further postulates that the most appropriate treatment process of waste water depends on the physical and chemical characteristics of the water. In Zimbabwe, most gold processes make use of chemical techniques, for example addition of ferrous sulphate, to reduce the concentration of free cyanide. The other pollutants i.e. the heavy metals are not being controlled. The nature of pollutants depends on the geochemistry of the mined deposit as well as the mineral extraction route followed (Love et al. 2006). At a gold mine in Zimbabwe, effluents are treated using ferrous sulphate to reduce cyanide levels from a range of 280 – 320mg/l to levels lower than 0.06mg/l before disposal. The Environmental Management Agency (EMA) in Zimbabwe has set the legal environmentally friendly cyanide concentration at 0.07 mg/l. However, it is noted that severe environmental impacts result from the other components of the effluent.

3. RESEARCH QUESTIONS

1. What are the main pollutants from gold cyanidation plants?
2. How are pollutants from tailings dams dispersed in the environment?
3. What is the relationship of tailings constituents and the environmental impacts?

4. LITERATURE REVIEW

This section reviews literature on gold extraction, cyanidation process, pollutants from gold recovery process and heavy metals.

4.1 Gold recovery overview

Physico-chemical parameters consistently captured and selected as crucial are; electrical conductivity, total dissolved solids, pH, biochemical oxygen demand and turbidity.

How mine’s tailings dam number 5 is consistently being monitored using three water sampling points i.e. tailings dam process water, see-page water and the down-stream water. Furthermore, there is also one borehole located on the down side of the dam to cater for ground water monitoring. It was noted with concern that the process effluent stream is not being included as part of the monitoring program. At most mines, quarterly samples are taken and analysed as part of EMA compliance requirements.

4.2 Environmental Quality Standards

Environmental Management Agency (EMA) is the local body responsible for regulating the disposal of waste (solid waste and effluent), in Zimbabwe. TheEnvironmental Management Act Chapter 20:27 No. 12 of 2002 is the legislation which administers the management of effluent and solid waste (Ndlovu, 2016). Furthermore, the same author indicated the roles of the act as; formulation of procedures for prevention of pollution and environmental degradation and the enforcement of closely monitoring measures to oversee waste management that comprises generation, collection, processing, transportation and disposal of the waste.

Table1 summarizes the discharge limits for the effluent and solid waste. The discharge limits include heavy metals, physical and chemical properties of the waste effluent. EMA uses polluter pays principle through licensing which is according to the following four categories below: (ema.co.zw accessed 21/04/2017).

- **Blue** – in respect of a disposal which is considered to be environmentally safe.
- **Green** - in respect of disposal that is considered to present a low environmental hazard
- **Yellow** - in respect of a disposal which is considered to present a medium environmental hazard and
- **Red -** in respect of a disposal that is considered to present a high environmental hazard.

According to Nhapi & Gijzen (2002) the “polluter pays principle” in the EMA is meant to guarantee that the individual causing the most pollution shall bear the largest load in paying for cleaning of the environment. Organizations or individuals must come up with strategies which avoids or minimize pollution of the environment. However, some entities are reluctant to embrace new technologies in the dimension of pollution prevention or minimization.

4.3 Environmental Pollution Simulation and Modeling

Schnoor (1996)specified three reasons for building mathematical models of the environmental pollutants and the reasons are: (1) to gain a better understanding of the fate and transport of chemical species in thesoil by quantifying their reactions, specification and movement. (2) to obtain chemical exposure concentrations to aquatic

Table 1: Effluent & Solid Waste Disposal. Source (EMA 2007)

		Blue		Green	Yellow	Red
Parameters	Units	Sensitive	Normal			
-	-					
Alkalinity	mg/l HCO_3	*	*	*	*	≤500
Arsenic	mg/l As	≤0.05	≤0.05	≤0.1	≤0.15	≤0.3
Biological oxygen Demand	mg/l	≤15	≤30	≤50	≤100	≤120
Chemical oxygen demand	mg/l	≤30	≤60	≤90	≤150	≤200
Cadmium	mg/l Cd	≤0.01	≤0.01	≤0.05	≤0.1	≤0.3
Calcium	mg/l Ca	*	*	*	*	*
Cobalt	mg/l Co	*	*	*	*	≤2
Chloride	mg/l Cl	≤200	≤250	≤300	≤400	≤500
Copper	mg/l Cu	≤1.0	≤1.0	≤2.0	<3.0	<5.0
Free Cyanide	mg/l CN	≤0.07	<0.07	≤0.1	≤0.15	≤0.3
Chromium	mg/l Cr6+	≤0.05	≤0.05	≤0.1	≤0.2	≤0.5
Dissolved oxygen	Saturation %	≥75	≥60	≥50	≥30	≥15
E. Conductivity	uS/cm	≤200	≤1000	≤2000	≤3000	≤3500
Iron	mg/l Fe	≤0.3	≤1.0	≤2.0	≤5.0	≤8.0
Grease & Oil	mg/l G&O	Nil	≤2.5	≤5	≤7.5	≤10
Magnesium	mg/l Mg	*	*	*	*	*
Manganese	mg/l Mn	≤0.1	≤0.1	≤0.3	≤0.4	≤0.5
Nickel	mg/l Ni	≤0.3	≤0.3	≤0.6	≤0.9	≤1.5
Lead	mg/l Pb	≤0.05	≤0.05	≤0.1	≤0.2	≤0.5
Nitrates	mg/l N	≤10	≤10	≤20	≤30	≤50
Mercury (Hg)	mg/l	≤0.01	≤0.01	≤0.02	≤0.03	≤0.05
pH		6.0-7.5	6.0-9.0	5-6 9-10	4-5 10-12	0-4 12-14
Oxygen absorbed(PV)	mg/l	≤5	≤10	≤15	≤25	≤40
Phosphates	mg/l P	≤0.5	≤0.5	≤1.5	≤3	≤5
Potassium	mg/l K	*	*	*	*	≤500
Sodium	mg/l Na	≤200	≤200	≤300	≤500	≤1000
Sulphate	mg/l SO4	≤100	≤250	≤300	≤400	≤500
Total Dissolved solids	mg/l	≤100	≤500	≤1500	≤2000	≤3000
Total Suspended Solids	mg/l	≤10	≤25	≤50	≤100	≤150
Total Hardness	mg/l $CaCO_3$	*	*	*	*	*
Turbidity	NTU	≤5	≤5	*	*	*
Zinc	mg/l Zn	≤0.3	≤0.5	≤4.0	≤5.0	≤15.0
Detegents		≤0.2	≤1.0	≤2	≤3	≤5
Sulphides	mg/l S	≤0.05	≤0.2	≤0.3	≤0.4	≤1

organisms and humans in the past, present, or future and (3) To predict forthcoming conditions under various loading scenarios or management action alternatives. In recent years, various models of the fate of metals in soils have been presented in the literature (Issa, 2008).

Bandela & Kosey (2014) identified two principal functions of water quality modeling as being: enhancing understanding of physical, chemical and biological processes, and supporting water quality management and decision-making. The same authors stated that even though linear regressions models are one of the oldest statistical modeling tools, their use are still applicable in many linear relationships. According to Wainwright & Mulligan (2004) models are viewed as supporting tools to other methods in order to gain understanding and hence they uniquely test our understanding. Furthermore, evaluation of whether the effects and outcomes are reproducible from the current knowledge of the processes or not can be done using models. The correlation coefficient measures the extent of association that exists between two variables i.e. the dependent and the independent variables. A higher value of the regression coefficient means a better and more useful fit of the regression variables(Kumar & Sinha 2010). Linear correlation is when an increase or decrease in the value of one parameter corresponds with an equivalent increase or decrease in the value of the other parameter (Patil & Patil 2011). Chaubey & Patil (2015) in their study used the regression equation as a mathematical tool by substituting the values for the independent parameters in the equations they computed diverse dependent characteristics of water quality.

4. Leachability tests for tailings dam soil

Ermakov et al. (2007) postulate that the control of parameters that influence metal behaviour in the environment is very difficult, hence heavy metals migration and accumulation studies are demanding. According to Issa (2008), the following methods can be used to approximate the mobile, labile or bioavailable pools of metals in soil;

- single batch extraction of soil samples with salt solutions,
- sequential batch extractions with progressively strong lixiviants designed to solubilize metals ensembled in different solid matrices,
- isotope exchange methods,
- the diffusive gradients in thin films (DGT) technique, and
- column leaching experiments.

The most important parameters that influence leachability of metals from soils include; concentration of the leaching agent, pH, particle size of the soil grains, temperature and redox potential. A study was conducted by Han et al. (2016) at Jinya gold mine (China) to investigate the leaching characteristics of arsenic and antimony in tailings soil. The researchers used simulated rain water for leaching the waste and they found out that the elements dissolution was high. Similar column leaching experiments of tailings were done by Zheng et al. (2012) in China. Their results indicated lower concentrations of Cu, Pb, Cd, and Zn in leachates than those in the Chinese Quality Standard for Groundwater. However, Pb and Cd concentrations were below their detection limits as opposed to higher Cu and Zn leachate concentrations. Grover et al. (2016) investigated the leachability of gold tailings in the Witwatersrand Basin, South Africa, by rainwater. It was revealed that sulphates were the secondary mineral phases that hosted most of the soluble metals. Most bench-scale test-works done pointed out that, pH is a key parameter in the dissolution of heavy metals. Various metal ion species are thermodynamically stable at different pH and redox potential ranges. Therefore, it is essential to examine the influence of these parameters on the leachability of elements of a particular study area.

5. MATERIALS AND METHODS

5.1 Water samples

Water samples were taken using anacceptable water sampling procedure. Grab sampling was the main method applied to collect the samples. Water grab sampling refers to the collection of water samples from specific locations at specific times, without the use of automated sampling equipment (Washington Conservation District, 2007). Acid-washed and conditioned polypropylene 2.5 litre bottles were used to keep the samples for each point.Sampling areas for water and slurry were as follows; Upstream water, tailing dam water, see-page water and the downstream water.

5.2 Soil samples

For each sampling area, a total of fifteen grab samples were collected. Coning and quartering was used to subdivide the sampled material to get the final samples of; 1kg upstream soil, 5kg Tailings dam soil and 1kg Down-stream soil. Samples were collected both vertically and laterally. A hand auger and a shovel were the tools used in sampling and sample division. Soils were sampled on a depth of 0 to 30cm after removing a 2cm layer of debris. Polythene plastic bags were used as sample packs after removing air trapped inside. Soils were sampled from the following three areas; Upstream land, tailing dam and down-stream land.

5.3 Sample preparation and analysis

Samples were taken to the laboratory for preparation and analysis within twenty-four hours. The soil samples were dried, pulverized, acid digested and read using the Atomic Adsorption Spectrometer (AAS) machine(Varian Spectre AA 200 model). A particle size distribution analysis (PSD) was done on the soil using a series of sieves and a sieve shaker. Water samples were taken directly to AAS machine for reading after filtration. Sulphides were

analysed using the Ultraviolet Visible (UV/VIS) Spectrometer. The cyanide concentrations were determined using the titration method.Chemical analysis determination for the following ions; lead, chromium, iron, manganese, nickel, copper, arsenic, cobalt, cadmium, mercury, sodium, cyanide and sulphide was done. Figure 1 shows a mechanical sieve shaker and the stack of sieves at the Zimbabwe School of Mines fire assay laboratory. This was the equipment used in the determination of the particle size distribution of the tailings dam number. In the absence of the machine sieve shaker, researchers normally make use of manual shaking of the sieves which is however, a tedious process

Fig 1. Sieve shaker (ZSM Department of Metallurgy Laboratory)

5.3 Leachability tests

The aim of the test-work was to determine the dissolution and mobility rate of the heavy metals under different pH conditions. pH is

an important parameter which must be controlled before the discharge of the tailings effluent from the extraction plants. Natural conditions like rain can promote the dissolution and mobility of heavy metals from the tailings dam soil. A set of five, 500g batches of tailings dam soil samples were prepared. The soils were put in five separate leach columns. Leaching solutions were prepared using distilled water, hydrochloric acid and caustic soda according to Table 1 .

Table 1: pH preparation of leaching solution

Test No.	1	2	3	4	5
pH	3	5	7	9	11

To each column 500ml of distilled water with pH levels as indicated above were added from the top.Thepercolated solutions from the bottom of the columns were collected after twenty-four hours and analysed for the heavy metals and final pH.

5.4 Statistical Analysis

To complement the instantaneous samples collected, a five-year period (2012 to 2016) historical data on environmental monitoring was captured from the mine records. Over 25 parameters were captured on environmental regulations compliance. However, key variables were selected basing on the mineralogy of the ore being processed, consistency of recording and the criteria specified in literature sources. Seven heavy metals data which was selected and analysed included; iron, manganese, nickel, copper, zinc, sodium and sulphate. Physico-chemical parameters consistently captured and selected as crucial are; electrical conductivity, total dissolved solids, pH, biochemical oxygen demand and turbidity. In order to quantitatively evaluate the heavy metals and physico-chemical parameters, correlation analysis and regression equations were applied to the dataset. These tools helped in identifying the relationship between variables. MS Excel was used for all the statistical data analysis done.

6. RESULTS AND DISCUSSION

6.1 Correlation of heavy metals and other parameters

Correlation is the measure of the strength of relationships between a pair of variables. The higher the magnitude, the more the variables tend to move together in the direction specified by the sign of the computed correlation. A significant correlation has two possible interpretations i.e. one of the variables influences the other, implying that we can control the explained variable by managing the explaining variable. The relationship between the two A chemical analysis report was generated basing on 8 instantaneous water, pulp and soil samples which were collected on the slimes dam and surrounding environment on the 2nd of March 2017. This helped the researcher to verify the historical data supplied by the mine to assist in statistical analysis. A particular concern was to identify the key variables whose measurements lie outside EMA, environmentally friendly bands.Basing on the findings by Patil et al. can be explained by a mathematical equation called a regression model. (2012), where conductivity showed significant correlation with 10 other parameters, the researcher shall approximate the level of Total Dissolved Solids (TDS) at the reference point (seepage sampling point) as a function of various metals observed in the slimes dam. The correlation coefficients between thirteen (13) selected heavy metals and physico-chemical parameters of the study area were calculated and tabulated in Table 3.

Table 3. Correlation matrix for the tailings dam and seepage, selected water parameters

	Cu	*Fe*	*Na*	*Ni*	*TDS*	*Alk*	*Sulph*	*Amm*	*Fe(SP)*	*Mn(SP)*	*Ni(SP)*	*Sulph(SP)*	*TDS(SP)*
Cu	1.000												
Fe	0.829	1.000											
Na	0.763	0.930	1.000										
Ni	0.924	0.669	0.730	1.000									
TDS	0.755	0.645	0.801	0.901	1.000								
Alkalinity	0.987	0.829	0.767	0.925	0.763	1.000							
Sulphate	0.871	0.673	0.709	0.928	0.777	0.910	1.000						
Ammonia	0.678	0.960	0.851	0.475	0.507	0.693	0.490	1.000					
Fe(SP)	0.880	0.975	0.841	0.688	0.591	0.883	0.703	0.933	1.000				
Mn(SP)	0.763	0.990	0.928	0.589	0.593	0.753	0.583	0.964	0.945	1.000			
Ni(SP)	0.861	0.908	0.924	0.823	0.816	0.899	0.804	0.837	0.882	0.867	1.000		
Sulph(SP)	0.666	0.571	0.462	0.573	0.293	0.711	0.810	0.443	0.649	0.494	0.535	1.000	
TDS(SP)	0.754	0.476	0.248	0.611	0.316	0.757	0.659	0.382	0.648	0.376	0.438	0.726	1.0

NB:i. SP stands for seepage water parameters.

ii. All other parameters are for the tailings dam water.

The main focus on this analysis was to determine the relationship between parameters in the tailings dam water and the seepage (SP) water. Highly positive correlations (> 0.90) were observed between the following pairs: n(SP) and Fe (0.99), Mn(SP) and Ammonia (0.96), Mn(SP) and Na (0.92), Fe(SP) and Fe(0.975), Fe(SP) and Ammonia (0.93), Ni(SP) and Fe (0.908), and Ni(SP) and Na (0.92). Relatively weak correlations (<0.50) were found between the following variables: Sulphate(SP) and TDS (0.293), TDS(SP) and Na (0.248), TDS(SP) and Ammonia (0.382), and TDS(SP) and TDS (0.316). Furthermore, it can be observed that heavy metals i.e. manganese, iron and nickel in the seepage water stream have a high correlation value (> 0.80). This may be attributed to the release of the metals from a common source, i.e. dissolution of sulphide minerals within the tailings dam soil. Since a significant linear relationship exists amongst the variables, a panel of regression equations (Table 4) were estimated which explain the propagation of each of the parameters from the slimes dam to the see-page (SP) sampling points.The seepage water sampling point was chosen as the area representing the environment being impacted by the slimes dam water. The correlation matrix, Table 3, was used for the selection of parameters with higher value of correlation and a high level of significance for the regression models. According to literature sources, models with a high R square value are good. From the regression analysis, it was observed that manganese, nickel and iron in the see-page environment were the response variables mostly explained by a number of parameters in the slimes dam. On the other hand, it can be deduced that Ammonia, Alkalinity, Sodium, Iron, and Copper are the main independent variables in the tailings dam that can be used in explaining the environmental impacts. Different response (dependent) parameters of water quality can be computed by substituting the values ofexplanatory (independent) variables in the equations.

Figure 1 to Figure 5 represent the graphical correlations between some pairs of variables.Nickel levels in the see-page water are highly positively correlated with sodium in the tailings dam water as depicted in Figure 1. The R^2 value is 0.8529 indicating a high strength of the relationship between the two parameters. Figure 2 shows the relationship between manganese in the see-page water with the iron in the tailings dam water. A highly positive correlation exists with an R^2 value of 0.9809.Manganese in the see-page water and ammonia in the tailings dam water have a very high correlation as shown in Figure 3. Hence, ammonia concentration in the tailings dam water can be determined and used to predict the manganese in the see-page water.

Table 4. Regression equations for pairs of parameters with a high correlation

Pair of parameter	**R Square**	**P Value**	**F Value**	**Regression equation**
Mn(SP) & Ammonia	0.93	0.00045	66.5	Mn (SP) = -4.752 + 1.0506Ammonia
Mn(SP) and Fe	0.98	1.73e-05	256.2	Mn (SP) = 0.9284Fe
Mn(SP) and Na	0.86	0.002591	30.9	Mn (SP) = -8.359 + 0.1061Na
Mn(SP) and Cu	0.58	0.04587	6.98	Mn (SP) = 3.4019Cu
Fe(SP) and Fe	0.95	0.000187	96.2	Fe (SP)= 1.0574Fe
Fe(SP) and Ammonia	0.87	0.002139	33.7	Fe (SP) = 1.1761Ammonia
Fe(SP) and Alkalinity	0.78	0.0084	17.7	Fe (SP) = 0.03025Alkalinity
Fe(SP) and Cu	0.77	0.008942	17.2	Fe (SP) = 4.5384Cu
Fe(SP) and Na	0.71	0.01771	12.1	Fe (SP) = 0.1113Na
Ni(SP) and Na	0.85	0.002979	29	Ni (SP) = 0.0086Na
Ni(SP) and Fe	0.83	0.004638	23.6	Ni (SP) = 0.006939Fe
Ni(SP) and Alkalinity	0.81	0.005961	21	Ni (SP) = 000217Alkalinity
Ni(SP) and Cu	0.74	0.01274	14.4	Ni (SP) = 0.03128Cu
Ni(SP) and Ammonia	0.70	0.01878	11.7	Ni (SP) = 007431Ammonia
Ni(SP) and Ni	0.68	0.02288	10.5	Ni (SP) = 0.1490Ni
Ni(SP) and TDS	0.67	0.02527	9.9	Ni (SP) = -0.1836TDS
TDS(SP) &Alkalinity	0.57	0.04871	6.7	TDS (SP) = 4493.95 + 1.5151Alkalinity
Sulphate(SP) Sulphate	0.66	0.02715	9.5	Sulphate(SP) = 1.06896Sulphate

* SP for seepage.

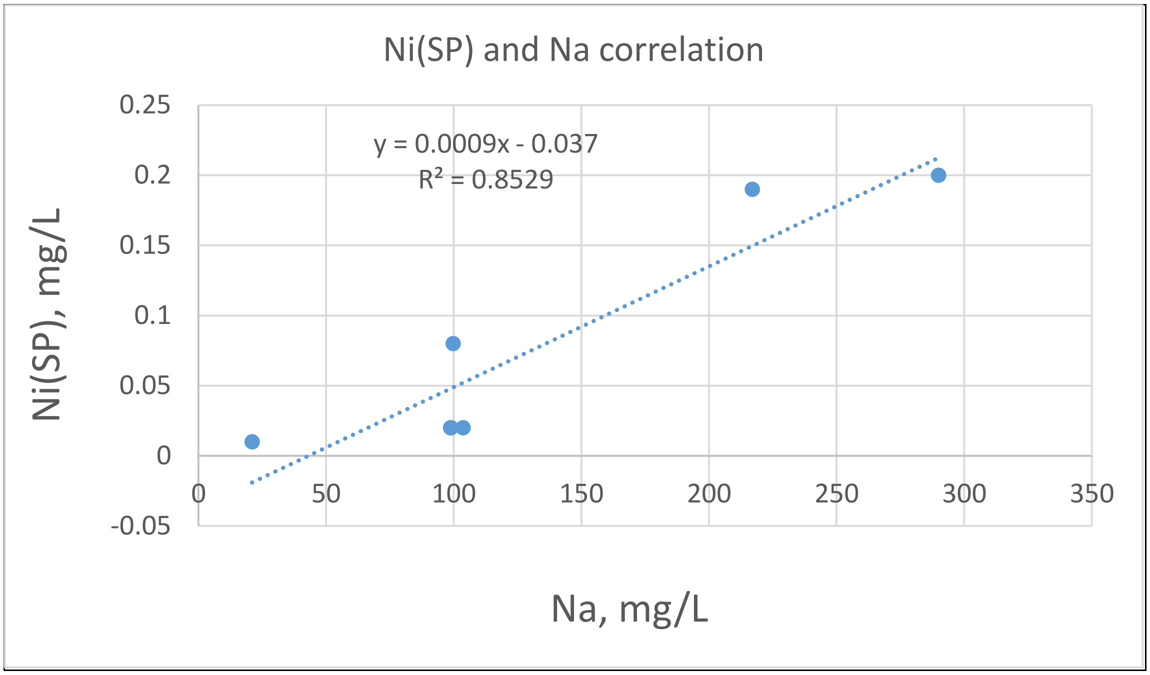

Fig 1.Correlation of Ni(SP) and Na

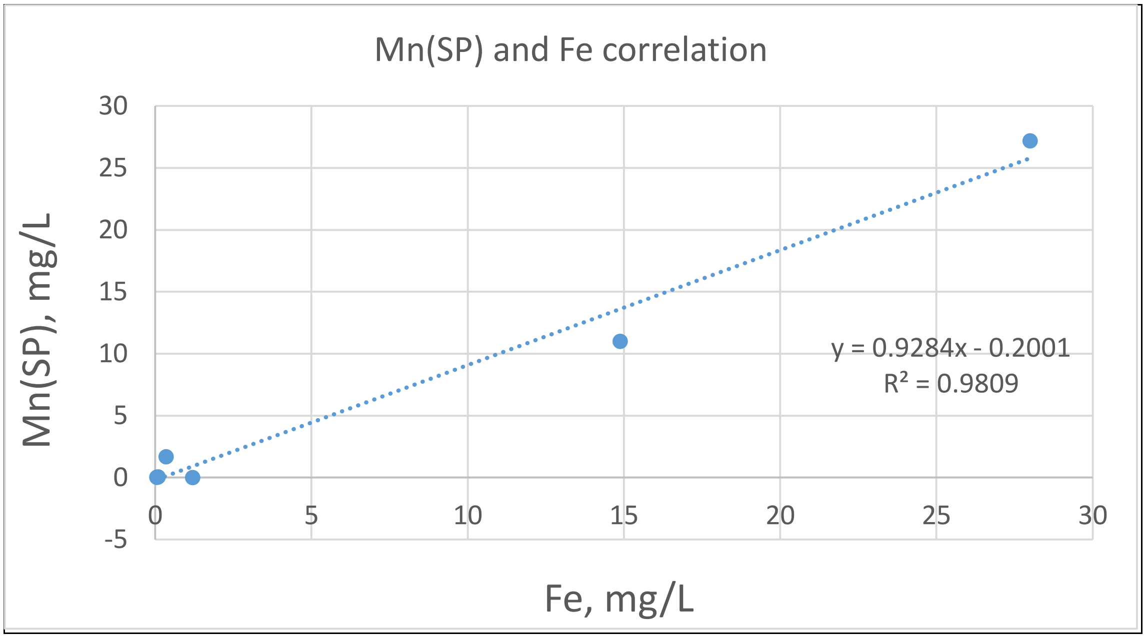

Fig 2. Correlation ofMn(SP) and Fe

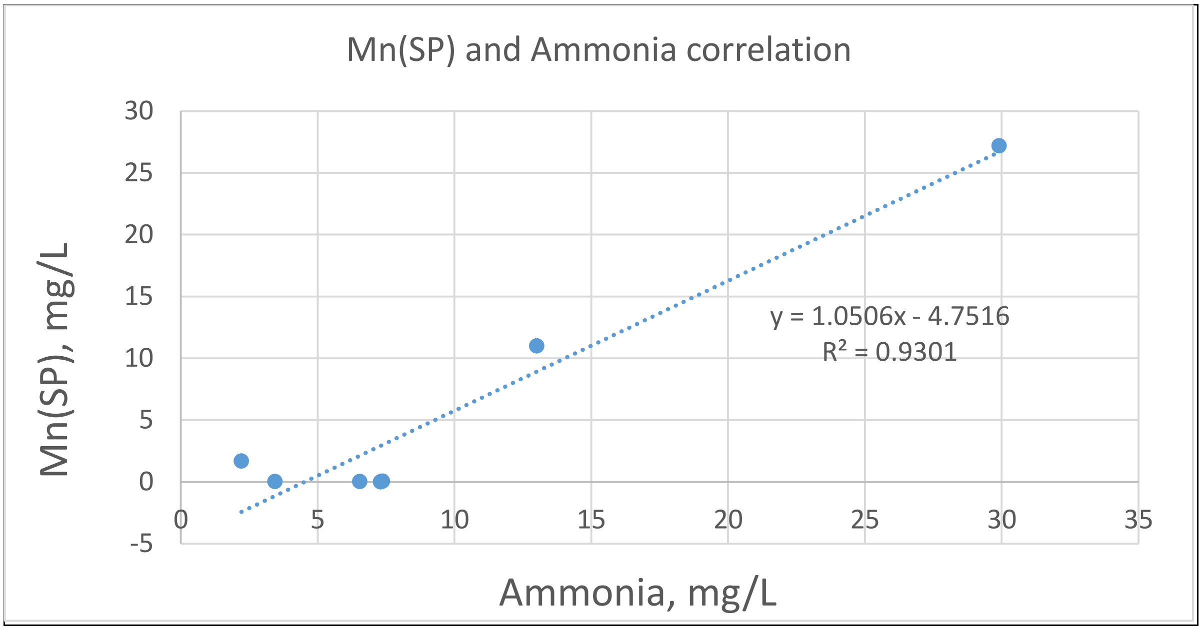

Fig 3. Correlation ofMn(SP) and Ammonia

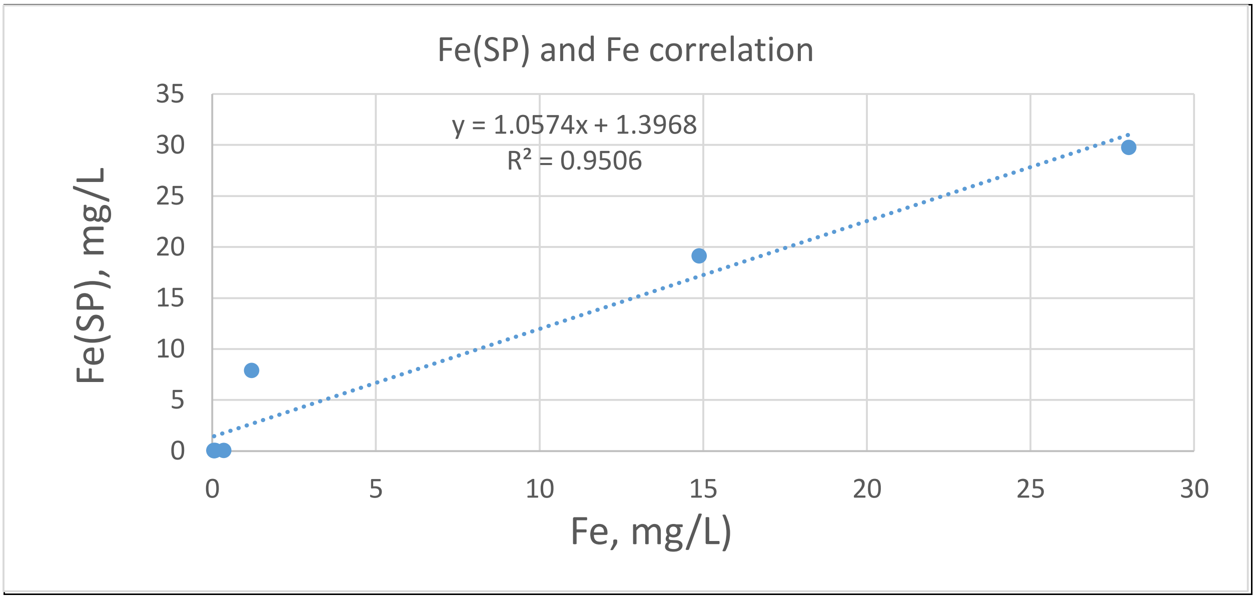

Fig 4.Correlation of Fe(SP) and Fe

Figure 4 represents the relationship of iron in the seepage (SP) water and the iron in the tailings dam water. It can be seen that there is a strongly positive relation between the two variables. Therefore, iron concentration in the tailings dam can be used to predict iron contamination in the environment, as represented by the see-page stream.Total dissolved solids(TDS) in the seepage water is related to the tailings dam water alkalinity as shown in Figure 5. From the R^2 value (0.5733) it can be deduced that there is a relatively weak correlation between the two variables.

In summary, different pairs of physico-chemical and heavy metal parameters of the study area indicated a significant linear relationship. The deduced regression equations are essential in estimating the quality of the environment after analysing a few variables. In the analysis, the see-page water stream represented the environment which is being impacted by the contaminants emanating from the tailings dam through infiltration of water. It can be concluded from the above analysis that manganese, iron and nickel in the see-page water can act as proxies for the environmental impact monitoring.

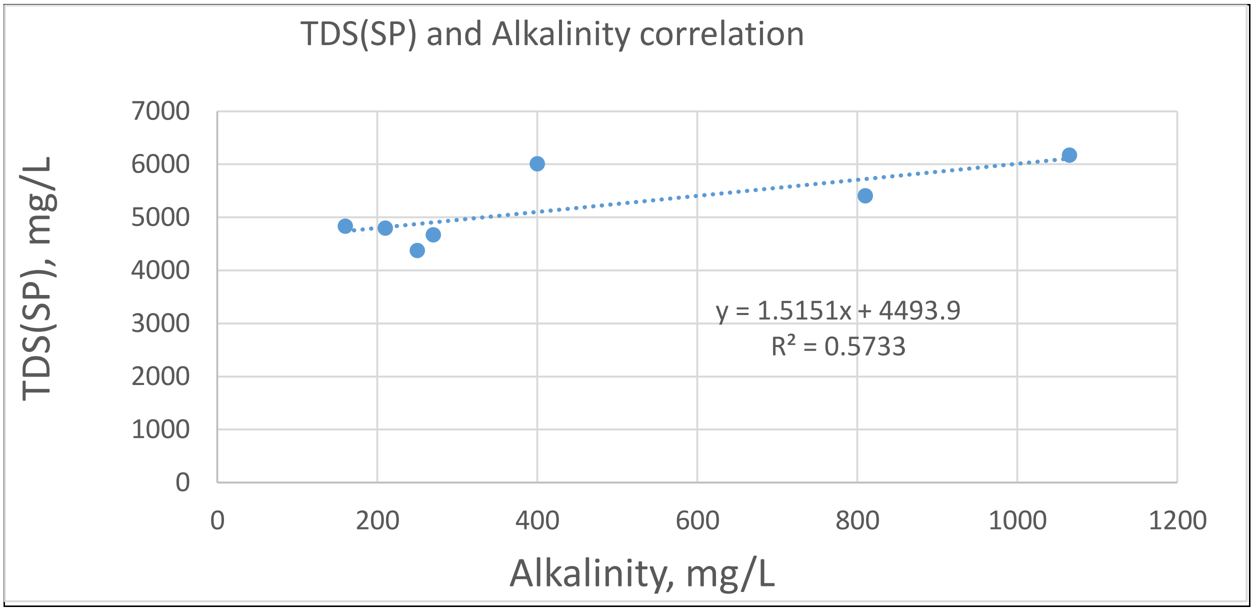

Fig 5.Correlation of TDS(SP) and Alkalinity

6.2 Leach Tests

6.2.1 Particle size distribution (PSD) analysis of Tailings dam soil

Particle size distribution is one of the key factors influencing the leachability and hence the mobility of heavy metals in particular sediments, soils or waste materials. Figure 6 depicts the particle size analysis of the tailings dam soil sampled that was used as the leach feed.

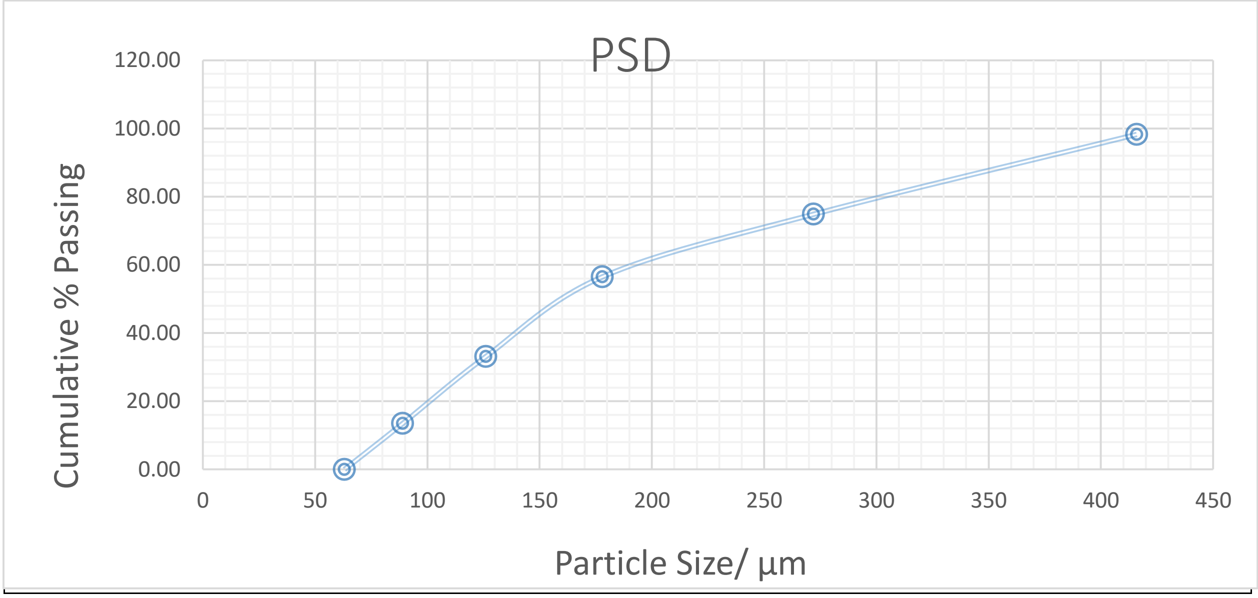

Figure6 Graph of particle size distribution (PSD) of tailings dam soil

6.2.2 Results of tailings dam soil particle size analysis

The particle size distribution (PSD) graph above shows that the grain size distribution of the tailings dam soil ranges from 63µm to 416 µm. The soil grains are relatively coarser, 50% passing 165µm, with an 80% passing 300µm size distribution. 6 % is finer than the 75µm (200 mesh) size and using the unified soil classification system (USCS), the soil is classified as coarse grained. Grain size determines the water drainage capacity and the exposed surface area for leaching agents in the environment. Presence of ultrafine particles in a particular soil may hinder drainage of water through the material and hence limit the mobility of soluble ions. Environmental contamination results when percolation of leachates occur in the tailings dam soil.

6.2.3 Results of Leachability Tests

Leachability test-works are important in showing the potential release of elements into aqueous solutions from the solid materials. The experiments of this study looked at the dissolution of manganese, arsenic, iron, chromium and lead under various pH conditions. These metals were selected on the basis that they were found to be very high in the tailings dam soil and at the same time significant amounts were detected in some water samples posing a high environmental hazard. The following results were obtained after a single batch 24-hour column leaching operation. Recovery in this case refers to the amount of a particular metal contained in the soil that is dissolved into solution expressed as a percentage of the initial total amount of that same metal in the soil.

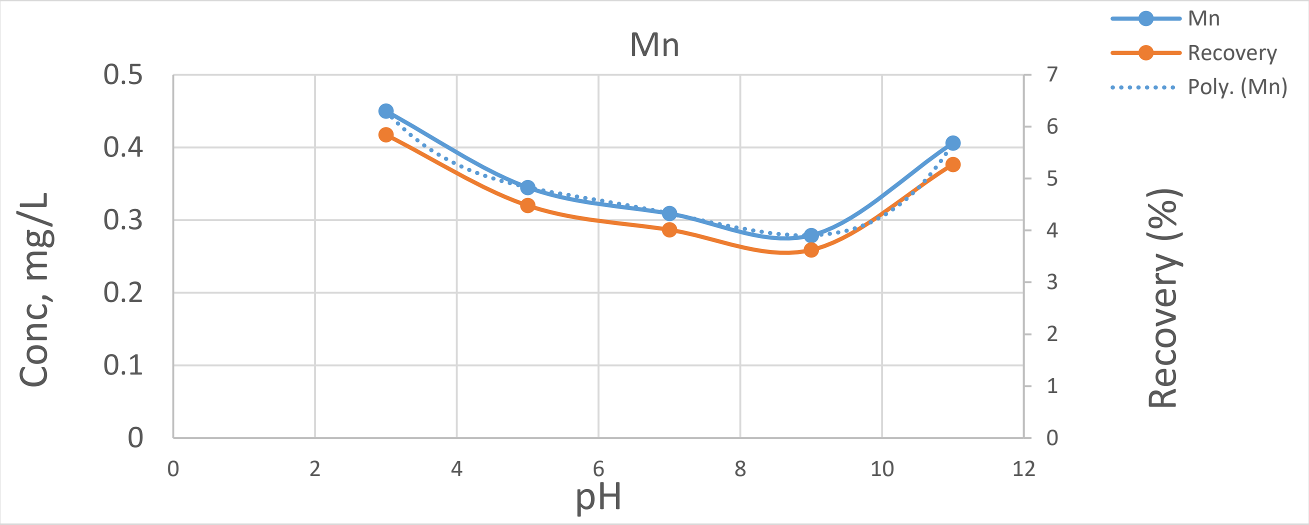

Fig 7. Manganese concentration and recovery after leaching

Figure 7 shows that the dissolution rate of manganese decrease as pH increase from the acidic range up to around 9. Leachability of the metal tends to increase in the alkaline pH range above 9 and is lowest in the near neutral range (7 to 9.5). The percentage extraction (recovery) ranged from 3.62 to 5.84% across the pH range investigated. This rate is high considering the EMA discharge limits, i.e. <= 0.1 mg/L for the environmentally friendly band. From the

trend above, the researcherestablished an interesting relationship between pH and Mn and a mathematical relationship between the two established. The coefficient of determination for the fit polynomial (dotted line) is tentatively 100%. A fitted polynomial equation that represent the dotted line graph was generated in excel and is given as;

$y = 0.0006x^4 - 0.0147x^3 + 0.1431x^2 - 0.6293x + 1.4013$……………………………..….**(1)**

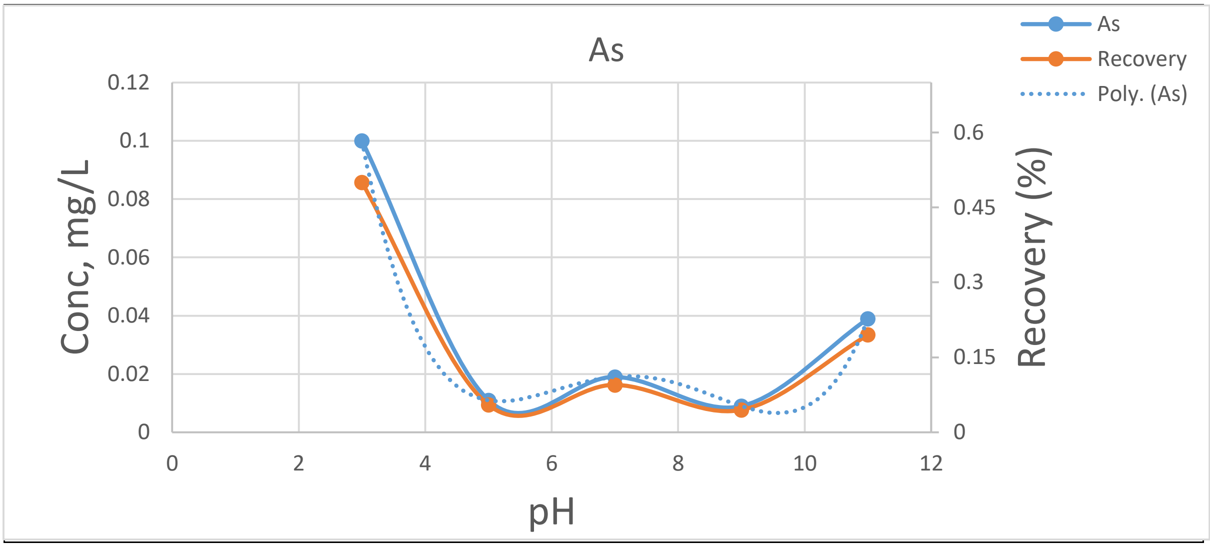

Fig 8. Arsenic concentration and recovery after leaching

The leaching behaviour of arsenic is depicted in Figure 8. From the graphs, it can be noted that lower dissolution rates are achieved in the pH range 5 to 9. However, it can be observed that there is a slight rise at neutral pH (around 7). Arsenic percentage extraction from the soil varied from 0.045 to 0.5 % across the pH array examined. Considering the higher toxicity hazard posed by this element, there is need to take action and prevent environmental contamination. The fitted polynomial equation generated in excel that represent the dotted line graph, is as follows;

$y = 0.0005x^4 - 0.0132x^3 + 0.1409x^2 - 0.6468x + 1.0927$……………………………….......**(2)**

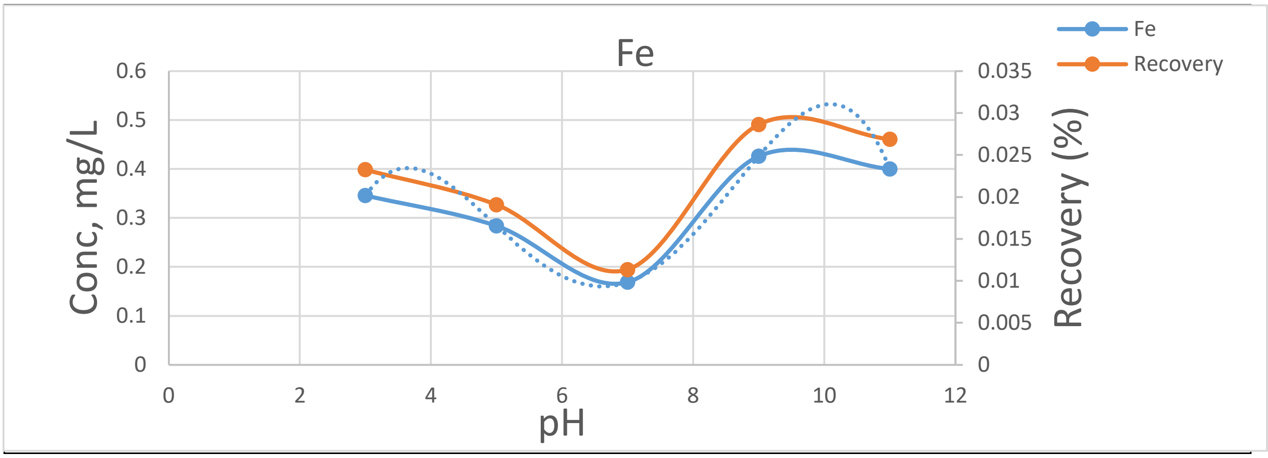

Fig 9. Graph of Iron concentration and recovery after leaching

Figure 9 represents the leaching behaviour of iron under various pH conditions. It can be observed that the dissolution is minimum at the neutral pH range (6 to 8). The extraction percentage ranged from 0.011 to 0.028 %. Though the dissolution rate is low, cumulative effects of the reactions can result in pollution of the biosphere especially at lower or higher pH values. The fitted polynomial equation that represent the dotted line in figure 6.9, is as follows;

$y = -0.0028x^4 + 0.0764x^3 - 0.7188x^2 + 2.7431x - 3.2479$……………………………......**(3)**

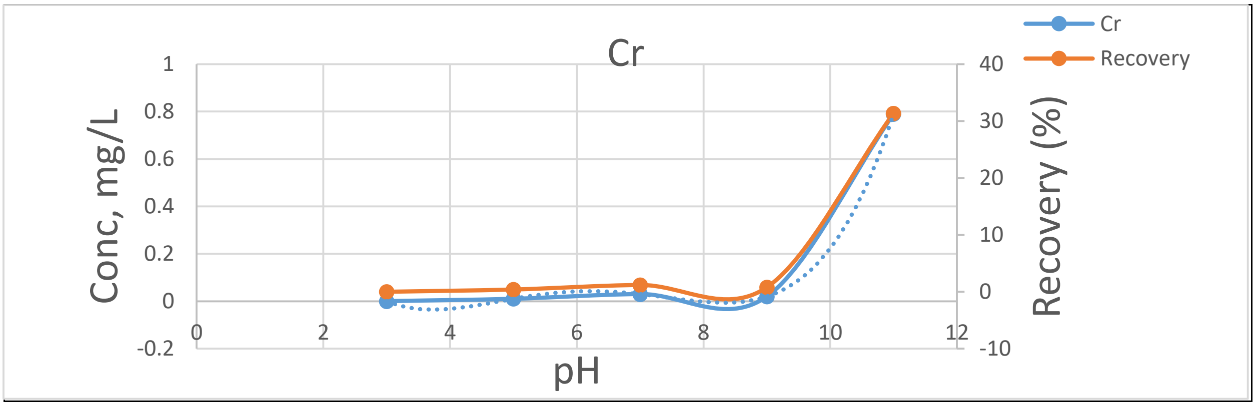

Fig 10. Chromium concentration and recovery after leaching

The leaching profile of chromium is shown in figure 6.10 above. The graphs indicate that the chromium extraction ranged from 0 to 31.35%. Chromium exhibited a low leaching profile from the acidic pH range to the neutral zone. A fitted polynomial equation that represent the dotted line graph was generated in excel and is given as;

$y = 0.0022x^4 - 0.054x^3 + 0.4697x^2 - 1.711x + 2.183$……………………………………..….**(4)**

Lead leaching profile is shown in figure 11 above. The metal dissolution trend exhibited in this investigation is ambiguous and further experimental examinations are required. Maximum percentage dissolution attained in the experiments is 2.2 at pH 3. The graphs indicate that lead has a very low leachability window across the pH range. This possibly explains the low concentrations of the metal in the tailings dam and its surroundings despite its higher levels in the tailings dam soil.

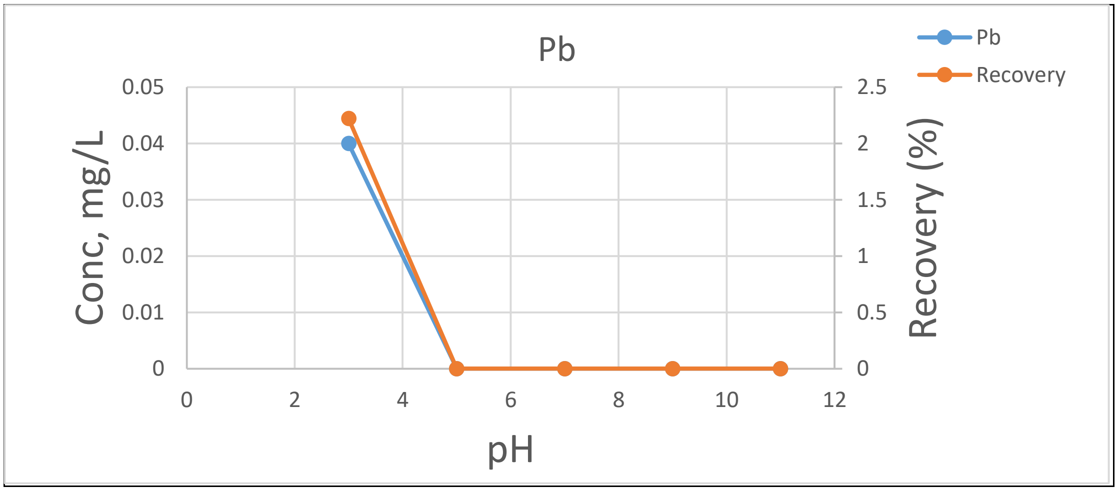

Fig 11, Lead concentration and recovery after leaching

7. Conclusions

This study investigated heavy metals contamination in tailings damsand surrounding areas of gold cyanidation plants in Zimbabwe. Correlation and regression analysis were done to explain the relationship between environmental parameters of the tailings dam water and the surrounding see-page stream. Highly positive correlations (> 0.90) were observed between the following pairs; Mn(SP) and Fe

(0.99), Mn(SP) and Ammonia (0.96), Mn(SP) and Na (0.92), Fe(SP) and Fe(0.975), Fe(SP) and Ammonia (0.93), Ni(SP) and Fe (0.908), and Ni(SP) and Na (0.92). Relatively weak correlations (<0.50) were found between the following variables; Sulphate(SP) and TDS (0.293), TDS(SP) and Na (0.248), TDS(SP) and Ammonia (0.382), and TDS(SP) and TDS (0.316). It was also deduced that heavy metals; manganese, iron and nickel in the see-page water stream have a high correlation value (> 0.80). The findings indicate that these heavy metals are probably being released from a common source; dissolution of sulphide minerals within the tailings dam soil. Leachability tests done revealed that manganese had the highest extraction rate across the pH range investigated, having a maximum of 5.8% extraction (0.45mg/L) at pH 3. Arsenic, iron and chromium also showed significant concentrations in the leachate; 0.1mg/L at pH 3, 0.42mg/L at pH 9 and 0.79mg/L at pH 11, maxima concentrations respectively. It was concluded that a pH range of 6 to 9 proved to be the optimum in minimizing the heavy metals solubility.

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