

Enrichment of toxic elements and potential ecological risks from asbestos-bearing mine wastes

Jessica Schapira

University of the Witwatersrand

Robert Bolhar

`robert.bolhar@wits.ac.za`

University of the Witwatersrand

Sharad Master

University of the Witwatersrand

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Abstract

In developing countries, such as those in Africa, empirical data characterising the chemical composition and ecological and health risks of solid mine wastes, such as asbestos, remains limited. While the geological properties and carcinogenic risks of asbestos fibres have been long-known and well-researched, the potential ecological impacts of exposed asbestos mine wastes and asbestos-bearing geological deposits have remained largely unexplored. In this pilot study a preliminary assessment of heavy metal pollution from asbestos-mine wastes is presented using different pollution indices in the context of source contamination. The quantitative contamination indices (enrichment factor, geo-accumulation index:geo), contamination factor (Cf), degree of contamination (C-degree) and pollution load index (PLI), as well as ecological risks and hazards quotient (HQ), were determined for chrysotile, amosite, crocidolite and anthophyllite mine waste types. The results show that asbestos-bearing mine wastes are important reservoirs of potentially toxic elements, with elevated concentrations of metals such as Mg, Fe, Ni, Mn and Cu, several of which exceed South African soil guideline values and therefore present potential environmental and human health concerns. Pollution indices identified substantial contamination across all waste types, with chrysotile exhibiting extreme enrichment of Mg (EF = 42.5) and Ni (EF = 72.8), while anthophyllite showed extreme Cu enrichment (EF = 29.2), indicating a strong potential for metal release into surrounding environmental media. Ecological risk assessment identified anthophyllite as posing the greatest environmental risk (RI = 636–1251), primarily due to elevated Cu concentrations, whereas chrysotile presented a moderate ecological risk associated with Ni, and amosite and crocidolite generally posed low ecological risks. Hazard quotient values greater than one for several metals further indicate the potential for adverse human health effects following exposure. Collectively, these findings demonstrate that ecological contamination indices provide an effective first-order framework for evaluating the geo-toxicity of asbestos-bearing mine wastes and support their application in future monitoring, remediation, and comprehensive environmental risk assessments.

1. Introduction

One of the greatest life-threatening concerns related to mineral extraction relates to mine dumps, wastes, and tailings, as these remain a persistent environmental issue due to significant ecosystem pollution. The soil, air, aquatic and biotic environments as well as human health are severely affected by left-over mine wastes, in turn affecting the economy [1]. Heavy metal pollution of air, water and soil is currently one of the most challenging environmental concerns and has gained considerable interest in recent years [2]. This is attributed to the severe toxicity to the environment in general, and negative impacts on ecosystems and human health, in particular [3, 4]. Exposure of humans to heavy metals occurs through the inhalation of heavy metal-enriched airborne particles or via the consumption of contaminated food or water [5]. Cumulative behaviours in environmental systems, persistence in the environment, non-degradable properties and extensive sources are some of the particularly concerning characteristics of potentially toxic metals (PTMs) [6, 7].

The growing public concern regarding the impact of heavy metals on human health and the environment has prompted increasing research involving the assessment of heavy metals contamination and health risks in soils [8, 9, 10, 11]. These studies quantified heavy metal concentrations in certain environments (typically soil and water), used pollution indices as proxies to heavy metal pollution in soils and estimated both the ecological and human health risks. Although such studies confirm pollution in the environment, they do not consider the source as the primary concern and how to prevent further contamination by release from the source, in most cases solid geological materials. To emphasise this, typically, heavy metals contamination studies focus on anthropogenic input sources, such as sewage sludges, fertilizers, atmospheric deposition from industrial sites, etc. However, contamination via the release of the geological source materials can pollute soils with concentrations that are 10–1000 greater [12, 13]. Thus, geochemical characterisation of heavy metals in waste rocks and mine tailings is essential for predicting potential sources of toxic metal pollution and initiating environmental policies.

Mine wastes are characterized as compositionally and mineralogically highly heterogeneous [14, 15]. Therefore, to manage solid mine waste efficiently and effectively, several analytical methods are needed to correctly define the elemental constituents, their concentrations, along with their independent and inter-related consequences. Enrichment factor, geo-accumulation index, contamination degree, ecological risk index and hazard quotient are among these analytical approaches regularly adopted by researchers to ascertain the potential ecological risks presented by various wastes [16] and the quality of environmental systems in terms of their pollution indices [17]. These indices are widely used as they provide comprehensive chemical characterization of wastes at low cost [18]. The concentrations of specific elements in soil and water are controlled by natural biological, atmospheric and geogenic processes and define natural background levels (NBLs) [19, 20]. Climate, water-rock interactions, rainfall, and residence time are all natural factors used to define the natural background levels [21]. Natural background levels provide geochemical baselines to outline natural discrepancies in the concentrations of components within the surficial environment [22].

Historical asbestos mining operations have left a legacy of widespread environmental contamination globally. However, in comparison to North America and Europe, the number of modern environmental asbestos exposure sources in rural provinces of South Africa remains considerable. Many potentially toxic heavy metals may be hosted in asbestos minerals from which they may be mobilised during the weathering of asbestos-bearing mine rock waste contaminating surrounding atmospheric, soil and water environments [23]. Small size and low density of asbestos fibres makes heavy metal evaluations of these mine wastes particularly important as wind and water allows for their readily release and rapid environmental dispersion. Apart from the few studies emphasising implications for toxicity/pathogenicity from the heavy metal content of asbestos fibres little work has been done on the ecological risks and human health assessment of asbestos mine wastes.

The anthophyllite asbestos sample evaluated in the current study is a subsample of material used previously to examine naturally occurring asbestos (NOA) and fibrous minerals in the mineralised metacarbonate rocks of the Guelb Moghrein deposit [24]. Herein, samples containing fibrous minerals

were analysed to understand their formation and geological occurrence. It was reported that fibrous and asbestiform minerals formed through fracture filling, recrystallisation, and replacement processes [24]. Rock chemistry and available open spaces were identified as key factors controlling mineral formation. The study also discovered the rare coexistence of fibrous siderite and anthophyllite. The presence of asbestiform siderite, anthophyllite and talc highlights potential environmental and health risks, emphasizing the need for further mineralogical research and hazard assessment [24].

The chrysotile, amosite and crocidolite asbestos samples investigated in the current paper were also previously reported [25]. The focus of this previous study was to evaluate the health and environmental risks associated with derelict asbestos mines in South Africa and Southern Africa. Three asbestos fibre types, namely chrysotile, amosite and crocidolite, were collected from the Havelock, Penge and Prieska mines. Chrysotile (Havelock mine) occurs within serpentinite bodies of the Swartkoppie Formation in the Barberton greenstone belt [26]. Its formation is linked to tectonic activity, serpentinization, metamorphism and deformation, resulting in cross-fibre asbestos veins within ultramafic rocks [25]. Amosite (Penge mine) occurs as layered seams within banded iron formations of the Penge Iron Formation near the Bushveld Complex [27]. Deposition was controlled by rock composition and metamorphic conditions, with fibrous amosite commonly occurring in magnetite-grunerite-rich bands and fibrous lenses [25]. Crocidolite (Prieska Mine) occurs as seams interbedded within banded iron formations, with extensive blue asbestos fields stretching hundreds of kilometres toward the Botswana border [28]. Using mineralogical and geochemical techniques, our previous study assessed fibre composition, durability and potential toxicity. The findings highlight significant human and environmental hazards posed by asbestos-contaminated mine waste and emphasize the importance of baseline data for rehabilitation and environmental management efforts [25].

The aim of current study is to determine the total concentration of potentially toxic heavy metals in some asbestos mine wastes to infer pollution and contamination levels. The rationale behind this research follows previous pioneering studies [29, 30, 31], which demonstrate the severe degree of heavy metals concentrations in asbestos minerals and their significance with respect to the environment. The objectives were to use single and integrated indices to evaluate the extent of contamination in different types of asbestos mine wastes and to determine the metal enrichment and potential ecological and human health risks of the heavy metal contents. Findings allow to predict probable detrimental environmental outcomes arising from neglected and improperly handled solid mine wastes. This study also allows identification of solid mine wastes as sources of contamination for different potentially toxic metals (PTMs), which is important to advance understanding of their extent and spatial distribution [32, 33, 34].

The present study should be regarded as a pilot investigation designed to evaluate the feasibility of applying ecological risk assessment principles to asbestos-bearing mine wastes rather than as a comprehensive assessment of all environmental and health risks associated with these materials. The primary objective was to determine whether established ecological assessment methodologies, including the evaluation of potentially toxic element enrichment and ecological risk indices, can provide

meaningful preliminary insights into contaminant behaviour and potential environmental impacts in asbestos mine waste settings. As a proof-of-concept study, the investigation was intentionally limited in spatial coverage, sampling density, temporal scope, and analytical parameters, providing an initial scientific basis for assessing the applicability of this approach. The findings therefore represent a preliminary evaluation that identifies trends, highlights potential areas of concern, and informs the development of more comprehensive future investigations. A full-scale assessment would require substantially expanded sampling across multiple seasons, more extensive geochemical and mineralogical characterization, contaminant bioavailability studies, ecological receptor assessments, and integration with human health risk assessments to provide a complete understanding of the environmental consequences of asbestos-bearing mine wastes. Consequently, the conclusions presented herein should be interpreted within the context of a pilot feasibility study intended to establish the scientific merit and practicality of applying ecological risk assessment frameworks to asbestos-bearing mining environments.

2. Materials and methods

2.1. Study area and sampling

Representative rock samples of four different asbestos mine wastes were investigated: (i) Chrysotile from Havelock Mine, Eswatini; (ii) amosite from Penge, Lydenberg District, South Africa; (iii) crocidolite from Prieska Division, Northern Cape, South Africa and (iv) anthophyllite from Guelb Moghrein Mine, Akjoujt, Mauritania (Table S1). The asbestos-bearing rock samples were collected from surface exposure at different mine sites (for the first three this was done during their operation and these samples were taken out of storage for this study). Samples comprise both the host rock and the asbestos mineral fibres. The samples were handled in a fume hood avoiding dust generation during preparation. The chrysotile, amosite, crocidolite and anthophyllite ores were physically separated as fibrous bundles from their hosting rock. Once separated, the fibres were disintegrated further to loosen their compaction to facilitate separation from one another as individual fibres for subsequent examination. Using stainless steel serrated tip forceps, the morphologically desired and intact asbestos fibres were handpicked and placed into sealable sterile plastic containers for geochemical analysis of specific asbestos sample aliquots. The bulk rock samples were split into two subsamples for analytical testing to obtain analytical replicate data.

2.2. Chemical analysis of asbestos

Major, minor and trace element concentrations were determined using X-ray fluorescence (PANalytical PW2404 X-ray spectrometer) at the Earth Observatory, University of the Witwatersrand, South Africa. Major elements were determined using the Norrish Fusion 1 technique [35] involving in-house correction procedures [36]. Sample weight of 0.35 g and a flux weight of 2.5 g were combined for fusion using Johnson Matthey Spectroflux 105 at 1100°C, and raw data corrected. Standard calibrations were made up using synthetic oxide mixtures, international standards as well as in-house controls. Calibration

standards include International Reference Materials USGS series (USA) and NIM series (South Africa). Pressed pellets were prepared for trace element analysis and the data corrected for matrix effects using Compton peak monitoring. The chemical analysis of chrysotile, crocidolite, amosite and anthophyllite is used for determining quantitative contamination indices of solid mine wastes.

2.3. Pollution Indices for assessing metal contamination in asbestos rock samples

The degree of contamination may be comprehensively evaluated with the use of pollution indices [37, 38], including the degree of degradation and the environmental risks [39]. Two groups of indices include individual and complex indices [40]. A geochemical background (GB) is required for calculation of pollution indices from which abnormal and/or enriched heavy metal concentrations may be distinguished [40, 41]. The chosen background levels are crustal abundances, WHO permissible limits in soils and UICC asbestos standards (compositions).

Enrichment factor (EF)

The enrichment factor was used to assess the degree of heavy metal pollutant enrichment. Using iron as a reference element [42], this factor was calculated by Eq. 1 [43]:

$$EF = \frac{(Mx*FeB)}{(Mb*Fex)} \text{ (Eq. 1),}$$

where Mx is the concentration of the heavy metal (mg/kg), FeB is the average continental crust abundance of iron (mg/kg), Mb is the average continental crust abundance of the heavy metal (mg/kg) and Fex is the concentration of iron in the sample (mg/kg). Using the approach [44], the enrichment factors are evaluated (table S2).

Geo-accumulation Index (I_{geo})

The I_{geo} allows the assessment of heavy metal contamination in soils and minerals by referencing the measured concentrations to a specified geochemical background. The Muller expression [45] was used to determine the geo-accumulation index values:

$$\text{Geo-accumulation index} = \log_2\left(\frac{C_n}{1.5*GB}\right) \text{ (Eq. 2),}$$

where C_n is the concentration of the individual heavy metal, GB is a constant geochemical background value of 1.5 that allows the variability of heavy metals due to natural processes by providing a lithogenic correction [46]. The values of I_{geo} for the asbestos minerals allow the different minerals to be divided into classes based on quality (table S3) [45, 47, 48].

Contamination factor (C_f)

Contamination factors are used to assess the degree of heavy metal contamination in the hosting rocks (i.e. the asbestos rock samples). The contamination factors were calculated using the equation given by [49]:

$$C_f = \frac{C_s}{C_b} \text{ (Eq. 3),}$$

where C_s is the concentration of the toxic metal in the asbestos and C_b is the concentration of toxic metal in the background sample [46].

Environmental geochemical studies are significantly influenced by the chosen background values [50]. The average crustal abundance values are primarily chosen as reference baselines in contamination studies [40, 51, 52]. The crustal abundance, WHO permissible limits and UICC asbestos standards, were all chosen to evaluate the degree of heavy metal contamination in the four samples (Table 1).

Table 1
Crustal abundance, WHO permissible limits and UICC asbestos standards.

Metal	Crustal abundance (mg/kg) [53]	Permissible limits in soils (mg/kg) (WHO) [54]	UICC standard asbestos samples (mg/kg) [55]			
			Chrysotile	Amosite	Crocidolite	Anthophyllite
Al	82300	-	15682	0	0	26074
Fe	56300	50000	35870	476065	512564	68595
Mn	950	2000	903	23242	1549	1936
Mg	23300	-	663310	112099	45105	479739
Cr	102	100	2600	< 15	< 15	1330
Co	25	50	103	25	20	70
Ni	84	50	1850	33	18	1125
Cu	60	100	7	16	8	30
Zn	70	300	< 3	16	14	234
Zr	165	-	15	20	10	15
Ba	425	9	< 20	< 20	< 20	< 20
Pb	14	100	38	11	6	< 5

To evaluate whether the three chosen background values are not unreasonably different, analysis of variance (ANOVA) was performed for statistical significance. The ANOVA results indicate that the mean values of all the background values are statistically equal with $\Pr(F_{\text{stat}} < F_{\text{critical}} | H_0) = \alpha$ ($\alpha = 0.05$). The contamination factor can be classified based on the level of contamination given in Table S4 [33].

Degree of contamination (C_{degree})

The degree of contamination equals the sum of the contamination factors and is calculated according to equation:

$$C_{\text{degree}} = \sum C_f = \frac{\sum C_s}{C_b} \text{ (Eq. 4)}$$

The classification of degrees of contamination based on C_d values are given in table S5.

Modified degree of contamination (mC_d)

The modified degree of contamination is the sum of the contamination factors divided by the number of heavy metals measured. The modified degree of contamination is given according to equation:

$$mC_d = \frac{\sum C_f}{n} \text{ (Eq. 5)}$$

The interpretation of contamination using modified degree of contamination values are given in Table S6.

Pollution load index (PLI)

The pollution load index was calculated using the equation [57, 58]:

$$PLI = (CF_1 * CF_2 * CF_3 \dots CF_n)^{1/n} \text{ (Eq. 6),}$$

With CF being the contamination factor of each metal in the asbestos fibres and n the number of toxic metals assessed. The interpretation of pollution load index based on the PLI values calculated are given in Table S7.

2.4. Ecological risk assessment

To evaluate the likelihood of unfavourable ecological effects through subjection to one or many of the heavy metal contaminants contained in the asbestos samples, the Potential Ecological Risk Index (PERI) was employed [59]. The linkage of toxicity level, heavy metal concentration and ecological sensitivity of heavy metals are comprehensively considered in this method [60, 61]. Contamination degree, toxic-response factor and potential ecological risk factor are the three basic modules to make up the Potential Ecological Risk Index [59].

Individual potential ecological risk factor

The potential risk index for individual heavy metal contaminants is calculated using Eq. 7 [62]:

$$E_r^i = T_r^i * C_f^i \text{ (Eq. 7),}$$

Where T_r^i is the toxic response factor for the individual heavy metal pollutants and C_f^i is the contamination factor for the given heavy metal. The classification of ecological risk level using potential ecological risk index (E_r^i) values are given in table S8.

Ecological risk index

The total risk index of potential ecological risks was calculated using Eq. 8 [62]:

$$RI = \sum_{i=1}^n E_r^i \text{ (Eq. 8),}$$

Where RI is the sum of all the potential risk factors for all the heavy metals measured in each of the samples. The ecological risk level interpretation of risk index (RI) values are given in table S9.

2.5. Health risk assessment

By examining the source rock material, a full human health risk assessment cannot be achieved when compared to dust, water, and soil samples. However, the human risk associated with the heavy metals can be assessed using the hazard quotient (HQ) [63, 64]. The HQ was calculated as the ratio of the elemental concentration (C_c) and the upper threshold values in the lungs (C_p) [65, 66].

$$HQ = \frac{C_c}{C_p} \text{ (Eq. 9)}$$

The concentration range value for metals (mg/kg) in normal lungs is given in Table S10.

2.6. Statistical analysis

Statistical analysis of the datasets was conducted using Microsoft Office Excel 2016. The concentrations of heavy metals, their enrichment factors, geo-accumulation indices, contamination factors and toxic responses for each sample was compared using Pearson's correlation matrix analysis. The pollution load index, contamination degree and potential ecological risk index were compared among the four different asbestos analyses using variance (ANOVA) and the Turkey (HSD) test, where significant differences existed.

3. Results

3.1. Major, minor and trace elements

The major and minor elements (Si, Al, Fe, Mn, Mg, Ca, Na and K) measured in chrysotile, amosite, crocidolite and anthophyllite asbestos enclosed in waste rocks from different mine sites as oxides by XRF are reported in table S11. The major and minor elements (Al, Fe, Mn, Mg and Ni) assessed in the pollution indices were converted from oxide weight percent to ppm concentrations. Table S12 shows the concentrations of the trace elements in each sample. The results show that trace element concentrations are highly variable amongst the different types of asbestos mine wastes.

3.2. Potentially toxic elements

The concentrations (ppm) of 12 potentially toxic elements (Al, Fe, Mn, Mg, Cr, Co, Ni, Cu, Zn, Zr, Ba and Pb) in chrysotile, amosite, crocidolite and anthophyllite mine waste are listed in Table 2.

Table 2
Chemical composition of heavy metals (mg/kg) in asbestos mine wastes.

Metal (mg/kg)	Chrysotile	Amosite	Crocidolite	Anthophyllite
Al	11147	6802	1322	1512
Fe	13988	289340	267940	238705
Mn	230	4987	465	11075
Mg	246200	35220	13449	106748
Cr	83	4	D.L.	D.L.
Co	52	D.L.	D.L.	D.L.
Ni	1518	51	11	43
Cu	21	63	35	7419
Zn	16	41	12	1
Zr	0.5	3	0.4	0.06
Ba	D.L.	28	1	D.L.
Pb	6.6	5	5	8
Average value (n = 2)				
D.L.: Detection Limit				

The means of three selected background values (crustal abundances, WHO permissible limits in soils and UICC asbestos standards) are statistically significant at the 0.05 level. The three sets of values were averaged to make direct comparisons between the mean (n = 2) concentrations. The mean concentrations of Mg and Ni (chrysotile), Fe (amosite and crocidolite) and Fe, Mn, and Cu (anthophyllite) in the asbestos mine wastes were significantly higher ($p < 0.05$) than their respective background values.

The results show that the average concentrations of heavy metals in each asbestos sample vary significantly and decrease in the order of: Chrysotile: Mg > Fe > Al > Ni > Mn > Cr > Co > Cu > Zn > Pb > Zr; amosite: Fe > Mg > Al > Mn > Ni > Zn > Cu > Ba > Pb > Cr, crocidolite: Fe > Mg > Al > Mn > Cu > Zn > Ni > Pb > Ba > Zr and anthophyllite: Fe > Mg > Mn > Cu > Al > Ni > Pb > Zn > Zr.

A general comparison between concentrations of metals in asbestos mine waste shows that certain heavy metals in each sample are significantly higher than their respective background levels. The

concentrations of Mg, Co and Ni are similar to crustal abundances; Al, Mg, Co, Ni and Zr are similar to permissible limits in soils, and Cu and Zn are similar to IUCC asbestos samples in chrysotile, but greater than those in their respective background levels. The concentrations of Fe, Mn and Mg are similar to crustal abundances; Al, Fe, Mn, Mg, Ni and Zr are similar to permissible limits in soils, and Al, Mn, Mg, Ni, Cu, Zn and Ba are similar to IUCC asbestos samples in amosite and are greater than background levels. The concentrations of Fe are similar to crustal abundances; Al, Fe and Mg are similar to permissible limits in soils, and Al, Fe, Mg and Cu are similar to IUCC asbestos samples in crocidolite and greater than background levels. The concentrations of Fe, Mn, Mg and Cu are similar to crustal abundances; Al, Fe, Mn, Mg and Cu are similar to permissible limits in soils and Fe, Mn, Cu and Pb are similar to IUCC asbestos samples in anthophyllite and greater than background levels.

The sum of element concentrations (ppm) of special interest in the four mine waste types is given in Table 3. Anthophyllite and then chrysotile rock wastes give the highest values for the summation of Cr, Co, Ni, Cu and Zn: 7463 and 1690 ppm, respectively. The sum of Ba and Pb is greatest in the amosite rock waste (33 ppm) with the values for chrysotile, crocidolite and anthophyllite rock wastes being also similar.

Table 3
Sum (Σ) of element concentration in milligrams per kilogram (mg/kg) of chrysotile, amosite, crocidolite and anthophyllite.

mg/kg	Chrysotile	Amosite	Crocidolite	Anthophyllite
$\Sigma(\text{Cr, Co, Ni, Cu, Zn})$	1690	132	58	7463
$\Sigma(\text{Cr, Co, Ni, Cu, Zn, Mn, Fe})$	15908	294459	268463	257243
$\Sigma(\text{Ba, Pb})$	6.6	33	6	8
$\Sigma(\text{Al, Fe, Mn, Cr, Co, Ni, Cu, Zn, Zr, Ba, Pb})$	27062	301324	269791	258763

The baseline or normal soil metal concentration range (ppm) and maximum permissible metal levels for South African soils are reported in the supplementary material (Table S13).

The Cr, Cu and Ni concentrations determined for the chrysotile rock waste are greater than the maximum permissible limits of metals in soils, with Ni being greater than the baseline soil metal concentration range for South African soils. The concentration of Ni and Cu in amosite, Cu in crocidolite and Pb and Cu in anthophyllite are greater than the maximum permissible levels.

3.3. Contamination level of heavy metals in different asbestos mine wastes

Pollution indices are used to make geochemical assessments of the degree of heavy metal enrichment in each of the samples. The enrichment factors of heavy metals in the four asbestos samples are given in Table 4.

Table 4
Enrichment factor values of the studied asbestos mine wastes.

Metal	Chrysotile	Amosite	Crocidolite	Anthophyllite
Al	0.55	0.02	0.0034	0.004
Fe	1	1	1	1
Mn	0.97	1.02	0.103	2.75
Mg	42.5	0.29	0.12	1.08
Cr	3.29	0.009	-	-
Co	8.46	-	-	-
Ni	72.8	0.2	0.03	0.12
Cu	1.48	0.12	0.12	29.2
Zn	0.93	0.12	0.04	0.004
Zr	0.012	0.004	0.0005	0.00009
Ba	-	0.01	0.0008	-
Pb	1.9	0.07	0.08	0.14
Total	134	2.86	1.5	34.3

Chrysotile records extreme magnesium (42.5) and nickel (72.8) enrichment, significantly high cobalt (8.46) enrichment and moderate chromium (3.29) enrichment. All the heavy metals measured in both amosite and crocidolite show minimal enrichment factors. Copper (29.2) is extremely enriched in anthophyllite accompanied by moderate manganese (2.75) enrichment. The elevated enrichment factors for the four asbestos samples indicate that these mine wastes, under suitable conditions, are capable of appreciably enhancing the surrounding environmental compartments with many pollutants.

The geo-accumulation indices of the metals in the four mine wastes are given in Table 5. These values are used to determine and define the heavy metal contamination in the asbestos mine wastes by comparing their measured metal concentrations to geochemical background values.

Table 5
Geo-accumulation indices of the metals in the studied asbestos
mine wastes.

Metal	Chrysotile	Amosite	Crocidolite	Anthophyllite
Al	-3.47	-4.18	-6.54	-6.35
Fe	-2.59	1.78	1.67	1.5
Mn	-2.63	1.81	-1.62	2.96
Mg	2.82	0.01	-1.38	1.61
Cr	-0.88	-5.05	-	-
Co	0.49	-	-	-
Ni	3.59	-1.298	-3.41	-1.52
Cu	-2.03	-1.29	-1.36	6.37
Zn	-2.7	-1.34	-3.05	-6.34
Zr	-8.98	-6.06	-9.35	-12.0
Ba	-	-4.5	-8.56	-
Pb	-1.67	-1.98	-2.05	-1.32

The geo-accumulation index of magnesium (2.82) and nickel (3.59) in chrysotile indicate that these metals are heavily accumulated. Amosite shows moderate accumulation of iron (1.78) and manganese (1.81), and crocidolite moderate accumulation of iron (1.67). Extremely heavy accumulation of aluminium (6.35) and copper (6.37), and moderate to heavy accumulation of iron (1.5), magnesium (1.61) and manganese (2.96), are noted for anthophyllite.

The contamination factors for the four mine wastes are given in Table 6, and represent the ratio of mean concentration of each element in the asbestos type to the respective background value.

Table 6
Contamination factors of the studied asbestos mine wastes.

Metals	Contamination factors (CF)			
	Chrysotile	Amosite	Crocidolite	Anthophyllite
Crustal abundance				
Al	0.14	0.08	0.02	0.02
Fe	0.25	5.14	4.76	4.24
Mn	0.24	5.25	0.49	11.7
Mg	10.6	1.51	0.58	4.58
Cr	0.82	0.05	-	-
Co	2.10	-	-	-
Ni	18.1	0.61	0.14	0.52
Cu	0.37	0.61	0.58	124
Zn	0.23	0.59	0.18	0.019
Zr	0.003	0.02	0.002	0.0004
Ba	-	0.07	0.004	-
Pb	0.47	0.38	0.36	0.6
Permissible limits				
Al	-	-	-	-
Fe	0.28	5.79	5.36	4.77
Mn	0.12	2.49	0.23	5.54
Mg	-	-	-	-
Cr	0.83	0.05	-	-
Co	1.05	-	-	-
Ni	30.4	1.03	0.24	0.88
Cu	0.22	0.368	0.35	74.2
Zn	0.05	0.14	0.04	0.004
Zr	-	-	-	-
Ba	-	3.13	0.19	-

Metals	Contamination factors (CF)			
	Chrysotile	Amosite	Crocidolite	Anthophyllite
Crustal abundance				
Pb	0.07	0.05	0.05	0.08
IUCC asbestos standards				
Al	0.71	-	-	0.06
Fe	0.39	0.61	0.523	3.48
Mn	0.25	0.22	0.30	5.72
Mg	0.37	0.31	0.30	0.22
Cr	0.03	0.31	-	-
Co	0.51	-	-	-
Ni	0.82	1.55	0.66	0.04
Cu	3.14	2.30	4.38	247
Zn	5.40	2.6	0.9	0.006
Zr	0.03	0.19	0.04	0.004
Ba	-	1.41	0.09	-
Pb	0.17	0.48	0.84	1.68

Chrysotile shows a very high degree of Ni (30.4) and Mg (10.6) contamination; a considerable degree of Zn (5.40) and Cu (3.14) contamination, and a low degree of Co (2.10) contamination. Amosite shows considerable degree of Fe (5.79), Mn (5.25) and Ba (3.13) contamination, and a low degree of Zn (2.6), Ni (1.55), Mg (1.51) and Cu (2.29) contamination. Crocidolite shows a considerable degree of Fe (5.36) and Cu (4.38) contamination. Anthophyllite demonstrated a very high degree of Cu (247) and Mn (11.7) contamination; a considerable degree of Fe (4.77) contamination and a low degree of Pb (1.68) contamination.

Values for degree of contamination in samples using respective background values are given in Table 7.

Table 7
Degree of contamination values of the studied asbestos mine wastes.

Background values used in contamination factor	Contamination degree (C_{degree})			
	Chrysotile	Amosite	Crocidolite	Anthophyllite
CF – C.A.	33.3	14.3	7.11	145
CF – P.L.	33.0	13.0	6.46	85.5
CF – IUCC	11.8	-	-	253
CF – C.A.: contamination factor using crustal abundance as background value (BV)				
CF – P.L.: contamination factor using permissible limits in soil as background value (BV)				
CF - IUCC: contamination factor using IUCC standard reference asbestos samples as background value (BV)				

Chrysotile shows a very high degree of contamination when both crustal abundance and WHO permissible limits are used as geochemical background values and a moderate degree of contamination when referenced against the IUCC chrysotile standard. Conversely, amosite shows a moderate degree of contamination using crustal abundance and WHO permissible limits as reference values. Crocidolite exhibits a low degree of contamination using crustal abundance and WHO permissible limits. A very high degree of contamination is noted for all three geochemical backgrounds in the anthophyllite sample.

Table 8
Modified degree of contamination values of the studied asbestos mine wastes for each background value.

	Chrysotile	Amosite	Crocidolite	Anthophyllite
Crustal abundances				
mC _d	3.03	1.3	0.7	16.1
Permissible limits				
mC _d	4.12	1.63	0.92	14.2
IUCC asbestos standards				
mC _d	1.07	-	-	28.7

The modified degree of contamination for chrysotile shows moderate, high and very low contamination for crustal abundance, permissible limits in soil and IUCC asbestos standard background levels, respectively. The modified degree of contamination for amosite and crocidolite shows very low and low contamination for crustal abundance and permissible limits,, respectively. The modified degree of contamination for anthophyllite shows extremely high, very high and extremely high contamination for

crustal abundance, permissible limits in soil and IUCC asbestos standard background levels, respectively.

Table 9
Pollution load index values of the studied asbestos mine wastes.

Reference values used	Chrysotile	Amosite	Crocidolite	Anthophyllite
Crustal abundances	0.48	0.37	0.13	0.47
Permissible limits in soil	0.4	0.53	0.24	0.91
IUCC standards for asbestos	0.39	1.52	0.92	0.36

The pollution load index values of all four asbestos samples using crustal abundance and WHO permissible limits as backgrounds all report as low, indicating immediate mitigation measures are not a necessity. Chrysotile, crocidolite and anthophyllite all report the same as above using IUCC standards as reference values. However, amosite is categorised for the existence of pollution.

3.4. Ecological risk assessment

The individual potential ecological risk coefficients (Er) and comprehensive potential ecological risk index (RI) values were calculated [59] to evaluate the potential ecological risk index of heavy metals in each type of asbestos waste.

Table 10
Individual potential ecological risk factors of the studied asbestos mine wastes.

Metal	Toxic response factors	CF – C.A.	CF - PL	CF – IUCC
Chrysotile				
Mn	1	0.2	0.1	0.3
Cr	2	1.6	1.7	0.06
Co	5	10.5	5.3	2.6
Ni	5	90.4	152	4.1
Cu	5	1.9	1.1	15.7
Zn	1	0.2	0.05	5.4
Pb	5	2.4	0.4	0.9
Amosite				
Mn	1	5.3	5.8	0.2
Cr	2	0.1	0.1	0.6
Co	5	-	-	-
Ni	5	3.05	5.1	7.8
Cu	5	3.07	1.8	11.5
Zn	1	0.6	0.1	2.6
Pb	5	1.9	0.3	2.4
Crocidolite				
Mn	1	0.5	5.4	0.3
Cr	2	-	-	-
Co	5	-	-	-
Ni	5	1.7	1.2	3.3
Cu	5	2.9	1.8	21.9
Zn	1	0.2	0.04	0.9
Pb	5	1.8	0.3	4.2
Anthophyllite				
Mn	1	11.7	4.8	5.7
Cr	2	-	-	-

Metal	Toxic response factors	CF – C.A.	CF - PL	CF – IUCC
Chrysotile				
Co	5	-	-	-
Ni	5	2.6	4.4	0.2
Cu	5	618	371	1237
Zn	1	0.2	0.004	0.006
Pb	5	3	0.4	8.4
CF – C.A.: Contamination factor using crustal abundance as background value CF – P.L.: Contamination factor using permissible limits in soil as background value CF – IUCC: Contamination factor using IUCC standard reference asbestos samples as background value				

Ecological risk level of nickel (152 ppm) in chrysotile is shown to be high and that of copper (1237 ppm) in anthophyllite considerable when referenced to crustal abundances. Conversely, both amosite and crocidolite indicate a low ecological risk level. The ecological risk levels of the four asbestos samples using WHO permissible limits are classified as identical to those of the crustal background abundances. The ecological risk level calculated for the samples with IUCC asbestos standard backgrounds indicate low risk for chrysotile, amosite and crocidolite. However, the copper level in anthophyllite is again demonstrated to be a serious ecological health risk.

Table 11
Ecological risk index values of the studied asbestos mine wastes.

Background value used in contamination factor	Potential ecological risk index (RI)			
	Chrysotile	Amosite	Crocidolite	Anthophyllite
CF – C.A.	107	13.9	6.07	636
CF – P.L.	160	13.2	8.60	381
CF – IUCC	28.9	25.1	30.6	1251
CF – C.A.: Contamination factor using crustal abundance as background value CF – P.L.: Contamination factor using permissible limits in soil as background value CF – IUCC: Contamination factor using IUCC standard reference asbestos samples as background value				

The results of the ecological risk index (RI) are very similar to those give above in the individual potential ecological risk factor. Using crustal abundance and IUCC asbestos standards as background values, chrysotile, amosite and crocidolite can be defined as low risk, whereas anthophyllite indicates a serious

ecological risk. Chrysotile can be characterised as a moderate ecological risk using permissible limit backgrounds, and amosite, crocidolite and anthophyllite are the same as the previous background values.

3.5. Health risk assessment

Values for Fe, Mn, Ni, Cu and Pb (mg/kg) of the four asbestos types are significantly greater than the concentration range of these elements in normal human lung tissue. The concentrations of Cr in chrysotile and amosite, Co in chrysotile, Zn and Ba in amosite all show values greater than those for normal human lungs. The health risks of the heavy metals contained in the asbestos mine wastes can be evaluated from their calculated hazard quotient (HQ) values given in Table 12.

Table 12
HQ values of the studied asbestos mine wastes.

Metal	Chrysotile	Amosite	Crocidolite	Anthophyllite
Fe	27.98	578.68	535.88	477.41
Mn	76.67	1662.33	155	3691.67
Cr	166	8	-	-
Co	520	-	-	-
Ni	1518	51	11	43
Cu	4.2	12.6	7	1483.8
Zn	0.53	1.37	0.4	0.03
Ba	-	25.45	0.91	-
Pb	13.2	10	10	16

Mg, Co and Ni in chrysotile, Fe, Mn and Mg in amosite, Fe in crocidolite and Fe, Mn, Mg and Cu in anthophyllite correspond to HQ values > 1, and therefore are considered to have adverse human health effects.

3.6. Statistical analysis

The inter-element associations between heavy metals in each rock sample is examined using a correlation matrix. Heavy metals that show high correlation coefficients may indicate similar origins; conversely, low correlation coefficients may reflect variable sources closely related to weathering processes [69]. Tables S14, S15, S16 and S17 in the supplementary material summarise the Pearson's correlation between metals within each sample at both $p < 0.05$ and $p < 0.01$ statistical significance. The correlation coefficient can be separated into four correlation classes: Low $r \leq 0.1$; medium $0.1 \leq r \leq 0.3$; high $0.3 \leq r \leq 0.5$ and very high $r \geq 0.5$ [70].

4. Discussion

Mining has emerged as a major cause for enhanced loading of metals to soil, water and atmospheric systems worldwide. Contributing to this problem is the inadequate and/or neglected management of exposed mine wastes. Increased weathering and metal leaching from these exposed metalliferous mine rocks, tailings and dumps are additional factors magnifying the anthropogenic introduction of heavy metals into the environment [71, 72, 73]. The present study focusses on the geo-toxicity of asbestos-bearing materials in the surface environment as hosts to large quantities of potentially toxic elements. Explanation of the heavy metal content of each asbestos mine waste is fundamental for determining the potential impact on public health and surrounding ecosystems. As geochemical data for South African metal-polluted regions come from geochemical research and characterisation of soil types, these values should only be considered as general estimates for the assessment of contamination [74]. A more accurate approach distinguishes contamination levels in the four asbestos rocks using pollution indices.

Significant quantities of potential toxic elements are hosted in solid mine wastes that, under conducive conditions, may be released into the surrounding environments, thereby altering their geochemical characteristics [75, 76, 77]. Chromium was detected in chrysotile rock waste in concentrations above permissible limits for soil. Intense gastrointestinal irritations are induced by toxic levels of Cr [78]. Copper was detected in chrysotile, amosite, crocidolite and anthophyllite rock wastes in concentrations above permissible limits for soil. Cu is an essential element for plants as it forms an important component of numerous proteins and enzymes required for their growth [78]. Although an essential element for humans' ingestion, Cu in excessive concentrations results in nerve laceration, fever, headaches and vomiting up blood [78]. Nickel was detected in chrysotile and amosite rock wastes at concentrations above permissible limits for South African soils. Nickel is a common and prominent metal found in water, soil, sediments and air [78]. Although not a cumulative toxin in humans, nasal sinus, chronic bronchitis and lung cancer are some health effects caused by the consumption of high levels of Ni [78]. Lead was detected in anthophyllite rock waste in concentrations above permissible limits for soil. Lead is a non-essential element having no biological function in animals or plants, but is extremely toxic to aquatic life and mammals [54, 79].

The present investigation was undertaken as a pilot study to evaluate whether established ecological contamination and risk assessment indices can be successfully applied to asbestos-bearing mine wastes as an initial screening tool for identifying the enrichment of potentially toxic elements and their relative ecological significance. Consequently, the study focused on determining the applicability of concentration-based geochemical indices, including the contamination factor, enrichment factor, geoaccumulation index, pollution load index, and potential ecological risk index, all of which are calculated from measured elemental concentrations relative to background values and do not incorporate environmental transport processes.

The results showed high concentrations of Fe, Mn, Mg, Al, Cu, Zn and Pb were observed in the asbestos mine wastes relative to background levels. Furthermore, higher contamination factors and geo-

accumulation indices are recorded in the four asbestos mine wastes compared to background levels. The higher enrichment factors, contamination factors and geo-accumulation indices demonstrated for various heavy metals in the four asbestos mine wastes provide evidence that they are heavy metal sources and indicate their potential to cause adverse effects on surrounding environments [16, 80, 81].

In environmental media the extent of heavy metal enrichment is commonly determined by the enrichment factor (EF) [48]. The asbestos mine wastes in the present study have EF values of Mg, Cr, Co, Ni, Cu and Pb greater than 1.5, indicating concentrations above background values [82] and suggesting high enrichment of these metals. It is evident that the degree of metal enrichment varies among the types of asbestos mine wastes, likely a result of the different processes accounting for their formation. The elevated EF values for the four asbestos mine wastes indicate, in general, that each of these solid wastes are, under conducive circumstances, able to notably enrich the encompassing environmental media [83]. Above mentioned concentrations of heavy metals have been known to have significant effects on plants, animals and humans [84, 85], such as DNA damage, cytoplasmic enzyme inhibition and carcinogenic effects in animals and plants [9].

High HQ values > 1 for the four asbestos mine wastes indicate that metal enrichment associated with their related locations is sufficient to induce significant human health effects. The asbestos mine waste type determines the health risks associated with the heavy metal contaminant enrichment.

The contamination and risk characterisation of the toxic elements measured in the four types of asbestos samples are summarised in the correlation matrixes. These matrixes are essentially the toxicity array identifying each of the measured heavy metals in terms of their concentrations, enrichment factors, geo-accumulation indices, contamination factors and toxic responses. The four-toxicity matrix is used as an initial approximation to classify the geo-toxicity of heavy metals in surface-exposed asbestos rocks and waste as a means of guiding future efforts. Calculation of indices linked to various features aids in establishing the suitable theoretical basis for appropriate interpretation of future soil conditions. Elements with high correlation values indicate that they may share a common source [86]. In soil, highly correlated elements indicate their alignment with their parent source [88]. Additionally, high correlation values between elements may exhibit analogous behaviours during transformation and migration processes [86]. Accordingly, the resources and their trajectories may be derived for inter-elemental relationships between different metals [87].

The ecological risk index (RI) and the human health hazard quotient (HQ) are complementary risk assessment tools that evaluate the implications of elevated heavy metal concentrations in mine wastes from ecological and human health perspectives, respectively. The ecological risk index (RI) and human health hazard quotient (HQ) demonstrate a strong overall relationship, indicating that asbestos-bearing mine wastes containing elevated concentrations of potentially toxic elements pose risks to both ecological receptors and human health, although the magnitude and dominant contaminants differ between the two assessment approaches. The RI evaluates the potential ecological effects of metals by integrating contamination factors with toxic response coefficients, whereas the HQ assesses the

potential for non-carcinogenic adverse health effects resulting from exposure to individual elements. Consequently, RI reflects the relative ecological sensitivity to contaminants, while HQ provides an estimate of potential human health impacts based on toxicological reference values. The correspondence between the two indices is particularly evident for anthophyllite mine waste, which exhibited the highest comprehensive ecological risk (RI = 636–1251 depending on the background value used) and simultaneously recorded HQ values greater than unity for Fe, Mn, Mg and especially Cu (HQ = 124). The exceptionally high ecological risk was almost entirely driven by the very large copper contamination factor and its high toxic response coefficient, while copper was likewise identified as the dominant contributor to potential human health risk. Similarly, chrysotile mine waste displayed moderate ecological risk (RI = 107–160) together with HQ values exceeding unity for Mg, Co and Ni, with nickel being the principal contributor to ecological risk owing to its elevated contamination factor and toxicity coefficient. In contrast, amosite and crocidolite generally exhibited low ecological risk indices, although HQ values greater than one for Fe, Mn and Mg in amosite and Fe in crocidolite indicate that individual metals may still pose potential health concerns despite relatively low overall ecological risk. The comparison demonstrates that elevated ecological risk does not necessarily translate directly into equivalent human health risk, because the two indices are based on different assessment frameworks and toxicological assumptions. The RI incorporates ecological toxic response factors and cumulative contamination to evaluate risks to environmental receptors, whereas HQ considers the potential adverse effects of individual elements on human health following exposure. Nevertheless, the agreement between the two approaches for chrysotile and particularly anthophyllite indicates that metals identified as major contributors to ecological risk, notably Ni in chrysotile and Cu in anthophyllite, are also the principal contaminants of concern for human health. These findings suggest that the ecological risk assessment provides an effective preliminary screening tool for identifying asbestos mine wastes requiring further investigation, while the HQ assessment complements this by identifying contaminants with the greatest potential to affect exposed human populations. Together, the RI and HQ results provide a consistent weight of evidence that anthophyllite and chrysotile mine wastes represent the greatest environmental concern among the asbestos waste types investigated and should therefore be prioritised for detailed exposure assessment, contaminant mobility studies, and site-specific risk management.

Overall, the findings of this study demonstrate that asbestos-bearing mine wastes represent not only a source of hazardous asbestos fibres but also a significant repository of potentially toxic elements capable of contributing to environmental contamination. The consistently elevated concentrations of several heavy metals, together with high enrichment factors, contamination factors, geo-accumulation indices, hazard quotients, and ecological risk indicators, provide robust evidence that these mine wastes have the potential to adversely affect surrounding terrestrial ecosystems and, under favourable weathering and transport conditions, pose risks to human health. Importantly, this study demonstrates the value of integrating established geochemical contamination indices with ecological risk assessment approaches to characterise the geo-toxicity of asbestos-bearing mine wastes, thereby expanding conventional asbestos investigations beyond fibre-related hazards alone. The toxicity matrices developed herein further provide a systematic framework for identifying priority contaminants,

evaluating inter-element relationships, and guiding future environmental monitoring and remediation strategies. As a pilot investigation, these findings establish the feasibility of applying ecological risk assessment principles to asbestos-bearing mine wastes and provide a scientific foundation for more comprehensive multidisciplinary studies incorporating mineralogical, geochemical, ecotoxicological, bioavailability, and human health assessments. Such integrated investigations will be essential for improving the long-term environmental management, rehabilitation, and risk-based regulation of asbestos mine waste sites in South Africa and other regions where legacy asbestos mining has left substantial volumes of exposed waste materials.

5. Research Innovations and Future Work

The present study is considered innovative because it extends established ecological risk assessment methodologies to a class of mining residues for which these approaches have not been systematically applied. Research on asbestos-bearing mine wastes has traditionally focused on the occurrence, mineralogical characterization, fibre release mechanisms, airborne exposure pathways, and associated human health risks, with comparatively limited attention given to the ecological implications of co-occurring potentially toxic elements within these waste materials. By applying ecological risk indices and enrichment factor calculations to asbestos-bearing mine wastes, this study introduces a novel framework for evaluating the environmental significance of metal and metalloid contamination associated with these deposits. This approach broadens the assessment of asbestos mine wastes beyond fibre-related hazards by incorporating ecological principles that are widely accepted in contaminated land and mine waste investigations but have not previously been applied directly to asbestos mining environments in an integrated manner. As such, the study represents a proof of concept that demonstrates the potential value of ecological risk assessment as a complementary tool for characterizing asbestos-bearing mine wastes.

The present study demonstrates that pollution and ecological risk indices can be successfully applied as preliminary screening tools for assessing potentially toxic elements in asbestos-bearing mine wastes. However, further research is required to develop a more comprehensive understanding of contaminant behaviour and environmental risk at derelict asbestos mine sites in South Africa. Future investigations should incorporate metal speciation and sequential extraction analyses to determine the geochemical phases, binding mechanisms, bioavailability, and mobility of potentially toxic elements associated with asbestos minerals and their host rocks. Measurements of physicochemical parameters, particularly pH, redox potential, electrical conductivity, and organic matter content, should be included to evaluate the influence of geochemical conditions on metal release and transport. Additional studies should investigate the spatial variability of contaminant concentrations across waste dumps and surrounding soils using high-density sampling strategies, together with assessments of the effects of natural weathering, mineral alteration, erosion, and leaching processes on contaminant mobilisation. Furthermore, the integration of regional climatic variables, hydrological processes, groundwater flow, surface runoff, and seasonal variability into ecological and human health risk assessments would improve understanding of contaminant transport pathways and long-term environmental fate.

Collectively, these multidisciplinary investigations would complement the concentration-based pollution indices presented in this study, reduce uncertainties associated with contaminant mobility and exposure, and provide a scientifically robust basis for environmental risk assessment, remediation prioritisation, and sustainable management of legacy asbestos mine sites in South Africa.

6. Conclusions

The environmental threats posed by asbestos mine wastes via heavy metal contamination into the surrounding environment is clearly demonstrated in this study. Four studied asbestos mine wastes show that they host heavy metals in considerable amounts, which can be leached out into and enriching surrounding environmental media. Site specific environmental management decisions are required as the type of asbestos mine waste determines the extent of heavy metal enrichment and associated potential ecological risk. The proportionally high concentrations of potentially toxic heavy metals measured in the asbestos rock waste samples make them reservoirs for toxic element enrichment and accumulation in soil and water. Ineffective environmental waste management of asbestos mine sites places the health of surrounding residents and environmental systems at great risk. To fully appreciate the progression of contamination in areas surrounding asbestos mine sites and waste storage facilities, greater focus should be placed on determining contaminant types and pollution extent at the source. This ultimately allows managements plans to be directed at reducing and containing the identified pollution at its origination before surrounding environments become contaminated. Given the preliminary nature of this work, additional research is required to validate the applicability of these methods across different geological settings, climatic conditions, waste types, and stages of mine weathering. Future investigations should also integrate ecological risk assessments with mineralogical, geochemical, ecotoxicological, and human health studies to establish robust, multidisciplinary frameworks for the environmental management of asbestos-bearing mine wastes.

Declarations

Author Contribution

All authors whose names appear on the submission made substantial contributions to the conception or design of the work or the acquisition, analysis, or interpretation of data; drafted the work or revised it critically for important intellectual content; approved the version to be published; and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Data Availability

Geochemical and mineralogical data were generated to form a basis for interpretation within the context of published research.

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