



Valorization potentials of phosphate tailings at Minjingu mines in Northern Tanzania

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Abstract

Sedimentary and igneous rocks are the two primary sources of phosphate that are mined and beneficiated to fertilizer. During the beneficiation process, phosphate is lost into the tailings. We investigated phosphate concentrations in tailings dumps at Minjingu mine, Tanzania using energy-dispersive X-ray fluorescence spectrometry to quantify the chemical compositions. The phosphate content in the tailings varied from 12.91% phosphorus pentoxide (P_2O_5) in Tailings 2 to 19.61% in Tailings Dump 1. The naturally occurring phosphate concentration in rocks ranges from 3% to 35%, and phosphate tailings from various locations with P_2O_5 concentrations as low as 6.46–12.65% have been beneficiated to commercial fertilizer. Our investigation revealed that phosphate concentrations in Minjingu tailings may be sufficient to be recovered for commercial applications. Suitable recovery methods are discussed, and we recommend that beneficiation should be performed to minimize the loss of phosphate into tailings. Further research is needed to identify the optimal beneficiation methodology.

Keywords

phosphate tailings, valorization, Minjingu mine, phosphorus pentoxide, beneficiation

Introduction

The main source of phosphorus and the primary raw material for manufacturing phosphate fertilizers is phosphate rock (Abouzeid, 2007; Farid et al., 2022). Most global phosphate ores originate from igneous and sedimentary deposits (Alsafasfeh and Alagha, 2017; Liang et al., 2018). Over 80% of phosphate fertilizers used globally are sourced from sedimentary phosphatic deposits (Derhy et al., 2020; El Bamiki et al., 2021). The concentration of phosphorus pentoxide (P_2O_5) in phosphate ores ranges from 3% to 35% (Notholt et al., 1979).

Phosphate deposits are mined using both opencast (or surface mining) and underground methods (Ptáček, 2016). The most common method is opencast mining, where the overburden is removed to uncover the phosphate reserve (Zhang, 2014). Bulldozers and excavators can be used to remove the topsoil, which can then be stored in stockpiles for later use, or used immediately at other reclamation sites (Mislevy et al., 2015; Toama, 2017).

The global demand for and production of phosphate fertilizers is increasing rapidly, while reserves continue to decrease (Oliveira et al., 2011; FAO, 2019; Safhi et al., 2022). Thus, the need to recover phosphate from tailings has become increasingly important (Jandieri, 2023). According to reserve assumptions and various scenarios for population growth, increasing demand for phosphate fertilizer has directly led to the depletion of phosphatic rock reserves (Wünscher, 2013). Gou et al (2019) reported that there is the possibility of phosphate being lost into tailings during the beneficiation process.

Phosphate tailings are industrial waste generated during the processing of phosphate ores into phosphate fertilizers (Chen et al., 2017). Tailings are widely recognized as a secondary source of phosphorus, which can be successfully utilized for the manufacture of phosphate fertilizer concentrates (Alsafasfeh and Alagha, 2017; Alsafasfeh et al., 2022).

Through beneficiation, the phosphate grade of the concentrate can be increased to between 28% and 35% P_2O_5 (Ravi et al., 2014; Boujlel et al., 2019; Alsafasfeh et al., 2022). Phosphatic rocks contain variable concentrations of phosphate minerals (Toama et al., 2015). Igneous phosphate rocks are typically low grade (< 5% P_2O_5) in comparison with sedimentary rock phosphates, but can be upgraded to 30% P_2O_5 (van Kauwenbergh, 2010).

Phosphatic rocks account for approximately 95% of global phosphate production. Some of the phosphate is lost in the tailings during beneficiation (Toamam et al., 2015). It has been demonstrated

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that up to 50% of the P_2O_5 can be lost during beneficiation (van Kauwenbergh, 2010). Taha et al. (2021) used column flotation to assess the efficiency of beneficiation at a fertilizer manufacturer in Brazil, and found that only 46.2% of the P_2O_5 was recovered.

In Tanzania, phosphate deposits are found in many different areas, and are of both igneous (Zizi, Ngualla, Panda Hill, Sangu-Ikola, and Nachendezwaya) and sedimentary (Minjingu, Chali Hill, and Chamoto) origin (Mchihyo, 1991; Jama and van Straaten, 2006). The Minjingu deposit comprises two types of phosphates, soft phosphate and hard phosphate, which both contain $> 20\%$ P_2O_5 and can easily be upgraded to 30% P_2O_5 by dry screening, making the resultant material suitable for direct fertilizer application (van Kauwenbergh, 1991; Szilas et al., 2008; Mwalongo et al., 2022).

Bulldozers and hydraulic excavators are used in the open-pit mining process at Minjingu Mines and Fertilizers Limited (MMFL); both for the removal of overburden (topsoil, clay, and sand layers) and the excavation of ore. Owing to the soft rock at MMFL, no drilling or blasting is necessary. The phosphatic materials are delivered by dump trucks to the pre-drying area, where they are spread out, crushed, and mixed by bulldozers. The waste clays are dumped in enormous piles. Before transportation to the beneficiation facility, the phosphatic materials must be dried to $< 15\%$ moisture (Szilas, 2002). Beneficiation is performed via physical separation rather than chemical means.

Crushing, grinding, screening, scrubbing, heavy media separation, washing, roasting, calcination, and flotation techniques are used to beneficiate low-grade phosphate ore (Liu et al., 2016; Ruan et al., 2019). Arroug et al. (2021) reported that low-grade tailings containing 15.84% P_2O_5 could be upgraded to 30.7% P_2O_5 using an organic acid leaching method. Li et al (2021) reported that low-grade phosphate with approximately 12.65% P_2O_5 was upgraded to 28.68% P_2O_5 using direct and reverse flotation. Teague and Lollback (2012) found that ultrafine phosphate tailings could be

upgraded from 6.46% to 34.7% P_2O_5 by flotation, and Alsafasfeh et al. (2022) obtained approximately 84.6% P_2O_5 recovery from tailings using direct froth flotation.

Khoshjavan and Rezai (2012), El-Midany et al (2013), Shariatiet al (2015), and Ismaila et al. (2020) have reported that phosphatic rocks with high CaO/P_2O_5 ratios can be beneficiated using calcination. Khoshjavan and Rezai (2012) upgraded low-grade phosphatic rock containing 11.9% P_2O_5 and 24.49% CaO to 31% P_2O_5 and 43.12% CaO via calcination and flotation. Ismaila et al. (2020) reported that calcination can be used to reduce the CaO/P_2O_5 ratio from 2.5 to 1.65 Shariatiet al (2015) indicated that low-grade phosphate deposits containing 9.16% P_2O_5 and 46.01% CaO could be upgraded to 30.77% P_2O_5 and 45.11% CaO using calcination and shaking table methods.

Little is known regarding the quantity of P_2O_5 present in Tanzanian phosphate tailings and how much may be recovered. Therefore, the purpose of this study was to evaluate the amount of phosphate in the tailings at MMFL in northern Tanzania.

Material and methods

The study area is located at Minjingu Hill, near Manyara Lake ($3^{\circ}42'21''-3^{\circ}42'3''$ S, $35^{\circ}54'56''-35^{\circ}54'14''$ E). Samples were taken from tailings situated near to the open pit (Figure 1).

Samples were collected at locations shown in Figure 2. There were five designated sample locations in each tailings dump. Three samples were collected at each designated sample location and composited. The samples were ground, dried, and split to obtain representative 50 g samples and packed into clean plastic bags (maximum capacity 1 kg) for analysis.

Sample preparation

All samples were sieved through a 60 μ m mesh and dried in an oven at 100°C. A total of 4 g of each sample was mixed with 0.9 g



Figure 1—Satellite images showing the geographical location of Minjingu Mines and Fertilizers Limited

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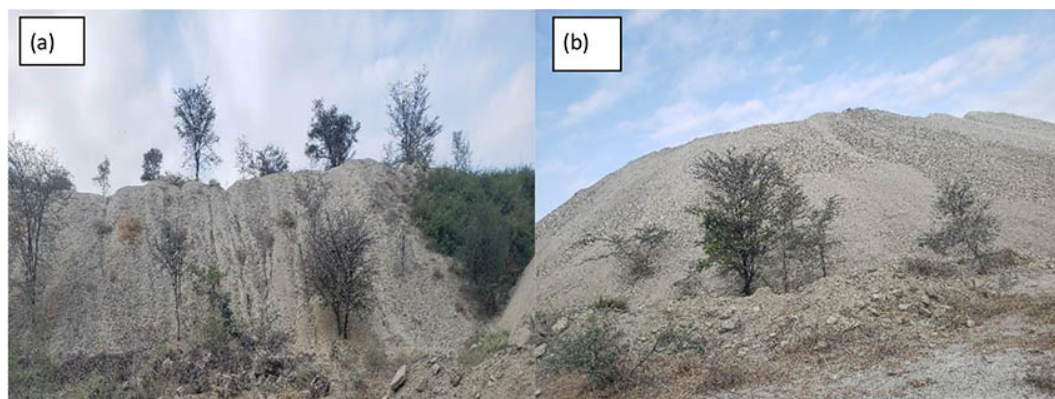


Figure 2— (a) Tailings dump 1 and (b) Tailings dump 2

of binder and pulverized for 10 min at 180 r/min. The pulverized material was placed in a cylindrical die of 32 mm diameter and pressed at a hydraulic pressure of 15 bar for 1 min to obtain a durable pellet for X-ray fluorescence (XRF) analysis.

X-ray analysis

Energy-dispersive XRF was used to identify the major elements in the pellets. The measurement time for all major elements in a given sample was approximately 900 s. Elemental concentrations were precisely calibrated using the International Atomic Energy Agency Certified Reference Material Soil 7 (CRM IAEA Soil 7).

Results and discussion

The accuracy of the XRF data was evaluated using the criterion for judging the acceptability of analytical methods (SR criterion) (Oscar et al., 2008):

$$SR = \{(C_x - C_w) + 2\sigma\}/C_w * 10, \quad [1]$$

where SR stands for standard random error, C_x represents the measured value, C_w is the certified value, and δ indicates the standard deviation of the experimental values.

According to this criterion, the difference between a certified value and an acquired analytical data-point can be separated into three categories: excellent ($SR \leq 25\%$), acceptable ($25\% < SR \leq 50\%$), and unacceptable ($SR > 50\%$). Table I presents data evaluated from three samples of the CRM IAEA Soil-7. The values for Mg, Al, Si, P, K, Ca, and Fe as determined by XRF were all in excellent agreement ($SR \leq 25\%$), but that for Na was unacceptable ($SR > 50\%$).

Our results revealed that Tailings dumps 1 and 2 had different concentrations of Na_2O , MgO , Al_2O_3 , SiO_2 , P_2O_5 , K_2O , CaO ,

Table I

X-ray fluorescence analysis of the International Atomic Energy Agency Certified Reference Material Soil 7, showing certified (C_w) and measured (C_x) values, standard deviation (SD), and standard random error (SR)

Element	Concentration (ppm)			
	C_w	C_x	SD	SR
Na	2 400.00	601.33	283.17	99
Mg	11 300.00	9 681.57	179.78	18
Al	47 000.00	47 102.80	292.75	1
Si	180 000.00	153 819.00	1 282.32	16
P	460	555.4	10.13	25
K	12 100.00	11 470.07	45.84	6
Ca	163 000.00	175 774.43	421.15	8
Fe	25 700.00	27 868.27	67.76	9

and Fe_2O_3 . The data are shown in Tables II and III, respectively. Typically, a greater R^2 value (closer to unity) equates to a better match between a regression model and the data. In this context, the certified and measured concentrations were shown to exhibit strong correlations (Figure 3).

Composition of phosphate tailings

Our elemental analysis results demonstrated that the tailings are mainly composed of CaO , P_2O_5 , SiO_2 , Na_2O , MgO , Al_2O_3 , Fe_2O_3 ,

Table II

Chemical composition of phosphate tailings in Dump 1

Sample	Chemical composition (%)							
	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	Fe_2O_3	CaO
TD11	10.58 ± 0.19	2.85 ± 0.04	1.03 ± 0.01	12.76 ± 0.17	18.58 ± 0.19	1.43 ± 0.02	1.48 ± 0.01	35.58 ± 0.3
TD12	13.68 ± 0.4	4.17 ± 0.04	1.51 ± 0.03	19.36 ± 0.12	16.34 ± 0.1	1.94 ± 0.01	1.99 ± 0.003	30.45 ± 0.12
TD13	10.57 ± 0.53	2.37 ± 0.02	0.69 ± 0.01	8.90 ± 0.05	19.45 ± 0.14	1.03 ± 0.01	1.07 ± 0.01	37.57 ± 0.26
TD14	13.74 ± 0.58	3.82 ± 0.08	1.42 ± 0.02	17.04 ± 0.08	17.47 ± 0.03	1.62 ± 0.004	1.7 ± 0.003	34.05 ± 0.1
TD15	13.4 ± 0.2	2.97 ± 0.04	1.27 ± 0.01	14.8 ± 0.08	17.24 ± 0.08	1.48 ± 0.01	1.52 ± 0.01	34.23 ± 0.21

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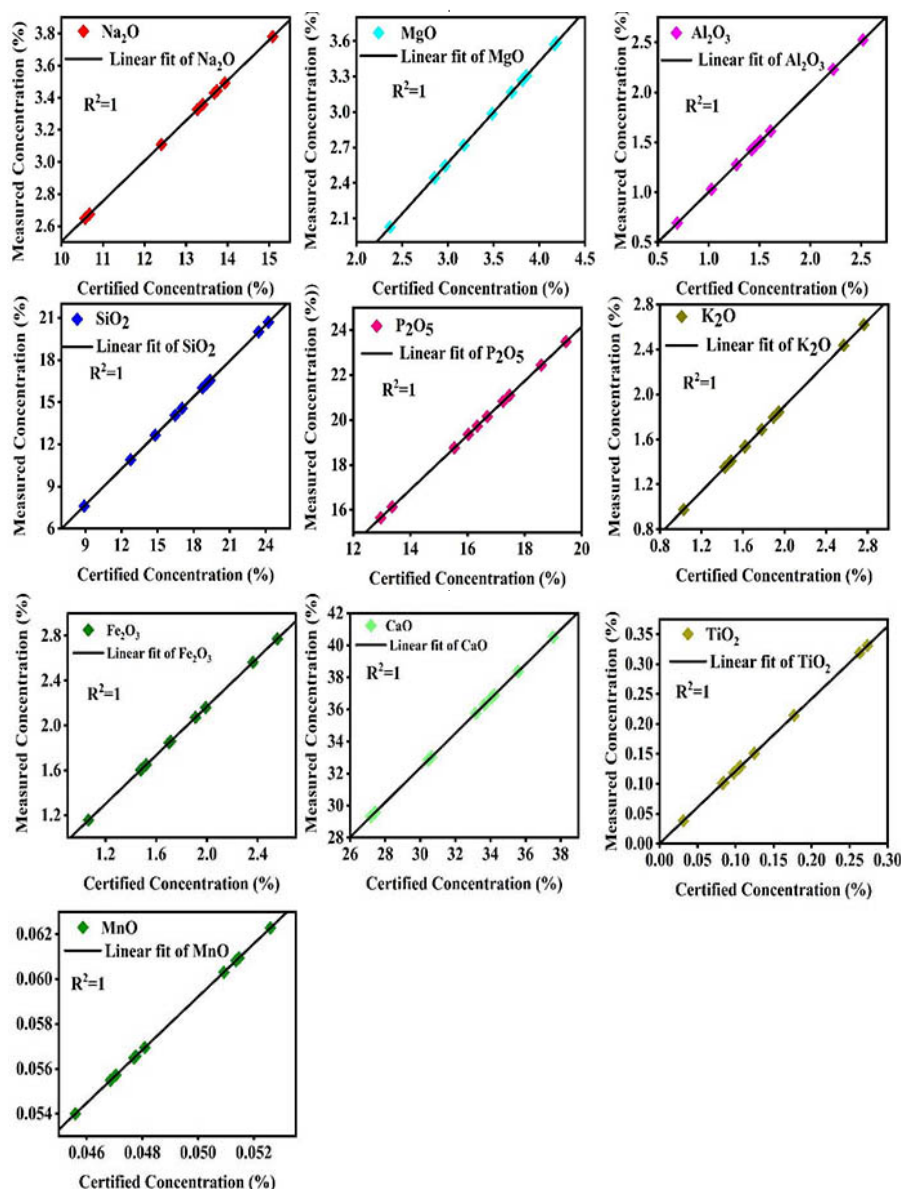


Figure 3—Correlations between measured and certified concentrations (%)

Table III
Chemical composition of phosphate tailings in Dump 2

Sample	Chemical composition (%)							
	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	Fe ₂ O ₃	CaO
TD21	10.68 ± 0.41	3.70 ± 0.01	2.23 ± 0.01	23.4 ± 0.06	12.96 ± 0.03	2.57 ± 0.004	2.36 ± 0.01	27.43 ± 0.11
TD22	12.41 ± 0.47	4.19 ± 0.04	2.52 ± 0.02	24.21 ± 0.2	13.36 ± 0.08	2.76 ± 0.02	2.56 ± 0.01	27.18 ± 0.14
TD23	15.09 ± 0.24	3.86 ± 0.05	1.61 ± 0.02	18.74 ± 0.2	16.69 ± 0.14	1.78 ± 0.02	1.49 ± 0.01	33.16 ± 0.22
TD24	13.93 ± 0.51	3.48 ± 0.09	1.61 ± 0.05	19.1 ± 0.09	15.54 ± 0.07	1.89 ± 0.01	1.91 ± 0.005	30.65 ± 0.13
TD25	13.27 ± 0.18	3.18 ± 0.03	1.45 ± 0.02	16.46 ± 0.02	16.03 ± 0.03	1.62 ± 0.01	1.71 ± 0.004	33.65 ± 0.14

and K₂O, as shown in Tables II and III. The lowest concentration of P₂O₅ was found in sample TD21 (12.96 ± 0.02%), and the highest in TD13 (19.45 ± 0.14%). The average P₂O₅ concentrations in Tailings dumps 1 and 2 were 17.82 ± 0.29% and 14.92 ± 0.40%, respectively. Because phosphatic rocks are the main source of phosphorus, the P₂O₅ concentration largely determines the ore quality (Mwalongo et

al., 2022). There are three different grades of phosphate ores based on P₂O₅ content: low grade (12%–16% P₂O₅), medium grade (17%–25% P₂O₅), and high grade (26%–35% P₂O₅) (Sengul et al., 2006). According to this classification, the samples from MMFL can be considered as low grade in Tailings dump 2 (Table III) and medium grade in Tailings dump 1 (Table II). The low levels of phosphates

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in the tailings reported herein are similar to previous findings in tailings from various other locations across the globe (Oliveira et al., 2011; Teague and Lollback, 2012; Shariati et al 2015; Arroug et al., 2021; Li et al 2021; Yang et al., 2021).

Conclusion

The tailings at Minjingu Mines and Fertilizers Limited (MMFL) contain elevated concentrations of Na₂O, P₂O₅, SiO₂, and CaO, with maximum values of 15.09 ± 0.24% (TD23), 19.45 ± 0.14% (TD13), 24.21 ± 0.20% (TD22), and 37.57 ± 0.26% (TD13), respectively. The lowest concentrations of Na₂O, P₂O₅, SiO₂, and CaO were 10.58 ± 0.19% (TD11), 12.96 ± 0.03% (TD21), 8.90 ± 0.05% (TD13), and 27.18 ± 0.14% (TD22), respectively. The present study, along with previous research conducted globally, indicates that the P₂O₅ concentration in MMFL tailings may be amenable to upgrading for the manufacture of commercial fertilizer. We recommend further research to explore an appropriate beneficiation technique for the recovery of phosphate fertilizers from these tailings.

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Author contributions

D. Mdachi: Conceptualization, funding acquisition, formal analysis, investigation, writing original draft preparation, visualization
A. Rugaika: Methodology, review and editing, supervision
R. Machunda: Methodology, validation, formal analysis, review and editing, supervision. All authors have read and approved the final manuscript.

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