Chemical and Mineralogical Characterization of Saudi-Pyrophyllite ore and its potential applications

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Abstract

Purpose: Due to the importance of pyrophyllite as an economical alternative to several minerals such as kaolin, talc, and feldspar in different industrial applications, there is an intention in Saudi Arabia to exploit pyrophyllite in the industry. Since there were no sufficient studies conducted to characterize pyrophyllite in Saudi Arabia, this paper aims to study the chemical and mineralogical characterization of Saudi pyrophyllite ore grades and propose its potential applications besides proposing beneficiation strategies for the low-grade one.

Method: In this study, two different grades pyrophyllite ore samples, from a pyrophyllite deposit in western Saudi Arabia, were characterized for their potential applications. Microscopic studies, X-ray fluorescence (XRF), scanning electron microscope coupled with energy dispersive X-ray (SEM-EDX), X-ray diffraction (XRD) were used for chemical and mineralogical characterization of the studied samples.

Results: Microscope and XRD results have shown that the ore samples (labeled grade A and grade B) consist mainly of pyrophyllite associated with quartz and feldspar in addition to minor amounts of muscovite, chlorite, and siderite as impurity minerals. Moreover, the results indicated that the impurities are oxide and sulfide minerals (i.e., pyrite, hematite). According to XRF analysis results, grade A contains high alumina (27.03% Al_2O_3) and low iron (0.4% Fe_2O_3) whereas; grade B contains a high iron content (2.06% Fe_2O_3) and lower alumina (24.05 % Al_2O_3). It is predicted that the grade A with high alumina content can be used directly in fillers, refractories, fiberglass, whiteware ceramics, white cement, porcelain, and cosmetic applications. As for grade B, high iron content limits its industrial applications. Therefore, it needs to be treated to remove ferrous impurities before supply to pyrophyllite market.

Conclusion: Based on analytical results, grade A with high alumina content can be used directly in fillers, refractories, fiberglass, whiteware ceramics, white cement, porcelain, and cosmetic applications. Furthermore, grade B needs to upgrade due to high iron content before being used in the industry.

Received: 15/12/2021
Revised: 10/01/2022
Accepted: 06/02/2022

Keywords: Pyrophyllite; low-grade; mineralogical; chemical; characterization; application; treatment.

Introduction

Pyrophyllite is a phyllosilicate mineral comprised mainly of aluminum silicate hydroxide [$Al_2Si_4O_{10}(OH)_2$] and is commonly found with other minerals such as talc and kaolinite, rutile, epidote, quartz, and mica (Abdrakhimova, 2010; Ali et al. ,2021; Jeong et al., 2017; Kogel et al.,2006)that will facilitate preparation of high quality acid-resistant materials. To advance cost-effective strategies for developing flat-sheet ceramic microfiltration membranes, the feasibility of using waste mineral-based materials as a ceramic membrane in engineered membrane bioreactor systems (MBRs). In its pure form, pyrophyllite is highly desirable in industrial applications for its specific properties (Bentayeb et al. ,2003; Evans and Guggenheim, 2018). It shows low electrical and thermal conductivity; low expansion; high refractive behavior; natural hydrophobicity; platy structure; inertness; low bulk density; low hot-load deformation; and high corrosion resistance to molten metal and gases (Zelazny and White ,2018). This mineral is widely used in refractory, ceramic, fiberglass, paper, paint, plastic, pesticide, fertilizer, rubber, roofing, and building material industries (Table1) (Ali et al., 2021; Harben ,2002; Jena et al. ,2015; Pradhan et al., 2015) ceramics and tile quality. We carried out the characterization of a pyrophyllite ore sample using optical microscopy, scanning electron microscopy, X-ray diffraction, Fourier transform infrared spectroscopy (FTIR). Furthermore, pyrophyllite has a lower expansion coefficient and thermal conductivity coefficient compared with other clay minerals. Therefore, it is suitable for refractory applications (Das and Mohanty, 2009; Dolley ,2013) .As a clay mineral, pyrophyllite can substitute kaolinite minerals in different industrial applications, such as ceramic, pottery, and filler industries, because kaolinite minerals are rapidly depleting and expensive (Ali et al., 2021; Mukhopadhyay, Ghatak, and Maiti ,2010; Pérez-Maqueda et al. ,2004) thermal expansion, infrared spectroscopy, DTA, XRD and SEM studies were also employed to understand the pyro-chemical properties of the specimen at different temperatures. The results indicate that the specimen contains pyrophyllite as major phase with sericite, quartz and diaspore as minor phases. Unlike kaolinite, pyrophyllite contains low alumina and high silica which on heating mainly produces mullite and amorphous silica. Mullite crystallization from pyrophyllite is rather easy than that from kaolinite. The silica in turn yields large amount of viscous liquid at high temperature. It is suggested that pyrophyllite may be utilized in such compositions favourably where mullite is a desirable phase by partial replacement of china clay which is a viable alternative particularly in the background of depleting reserves of kaolinite and its continuous cost escalation. Additionally amorphous silica produced in the reaction system may acts as an in situ produced filler material that reduces the use of quartz in such system. The differences on the thermal behaviour (DTG-DTA. Moreover, pyrophyllite can be alternative to talc in many applications, particularly as a filler in the pharmaceutical application, since pyrophyllite is safe in use and free from associated toxic minerals such as asbestos (Anja -Kostadinović et al., 2019). Pyrophyllite and talc have the same physical properties. Isomorphism exists between the two. Without a chemical test for aluminum, talc is virtually indistinguishable from pyrophyllite because it contains magnesium instead of aluminum (Das and Mohanty ,2009). Pyrophyllite world production is documented and presented in the graph (Figure 1).

Table 1. Common pyrophyllite applications.

Industry	Applications and Utilization of pyrophyllite	Ref.
Refractory	• Pyrophyllite is used as a refractory material. • Pyrophyllite-based refractories are used in iron and steel furnaces for lining purposes. • Also, it is used to make tile refractories, cement-fired bricks, fired brick-roofing, and special refractories.	(Ali et al. ,2021; Chen et al. ,2017; Shayakhmetov et al., 2018; Shymanskaya, Dyatlova, and Popov, 2019; Truong et al. ,2018)
Ceramic	• Pyrophyllite is used as a raw material in certain ceramic products. • Ceramic products containing pyrophyllite include tiles, sanitary ware, white ware, and electrical components (e.g., insulators, vacuum gaskets, resistors, and transducers).	(Ali et al. ,2021; Chatterjee ,2009; González-Miranda et al., 2018; Kairakbaev, Abdrakhimov et al., 2021; Kurnia et al., 2020; Mukhopadhyay et al., 2010)
Fiber glass	• Pyrophyllite is used as an alternative to feldspar in the glass industry as a source of aluminum. • Also, it is used to prepare fiberglass batches.	(Ali et al. 2021; ASTM ID:D5685-19., 2019; Elsandika et al. ,2016; Li ,2014; Seo et al., 2020)
Cosmetic industry	• The high purity pyrophyllite powder is used as a cosmetic.	(Ali et al.,2021; Fiume et al.. 2015; Pi-Puig, Animas-Torices, and ,Solé 2020; Pradhan et al., 2015; Steffen et al., 2020)
Paper	• High purity finely ground pyrophyllite is used as a filler in the paper industry and coating pigment.	(Hubbe and Gill ,2016; Kogel et al., 2006; Song, Wu, and Nie, 2020)
Plastic	• The medium purity is used as a filler material.	(Ali et al. 2021; Chatterjee, 2009; DeArmitt , 2017; Pradhan et al., 2015)
Paint	• The medium purity is used in paint. It can be utilized as a filler material, an extender, and a suspending agent.	(Ali et al. ,2021; Anon, 2014; Erdemoğlu et al., 2004; Kogel et al., 2006; McGonigle and Ciullo,1996)
Insecticide	• The low purity is used as a filler and as a carrier material in insecticide.	(Ali et al., 2021; Belzunces et al., 2017; Hasanbegović et al., 2021; Indian bureau of mines, 2017; Indian Bureau of Mines, 2019; Indian Bureau of Mines, 2018; Pradhan et al., 2015)
Fertilizer	• The low purity is used as a soil conditioner and as a fertilizer carrier.	(Adamović et al., 2020; Ali et al., 2021; Hasanbegović et al., 2021)
Rubber	• The low purity is used as a dusting agent in rubber.	(Chatterjee, 2009; Pradhan et al., 2015; Surya et al., 2021; Zhang et al., 2010; Ali et al., 2021)
Roofing	• The low purity is used as a dusting agent in roofing materials.	(Ali et al., 2021; Chen et al., 2020)
Others	• Pyrophyllite is used as an ornamental stone. • Pyrophyllite is used in carving handicrafts, wine glasses, chess boards, coasters, toys. • The medium purity is used in cement and building materials.	(Bakunov et al., 2013; Pradhan et al., 2015)

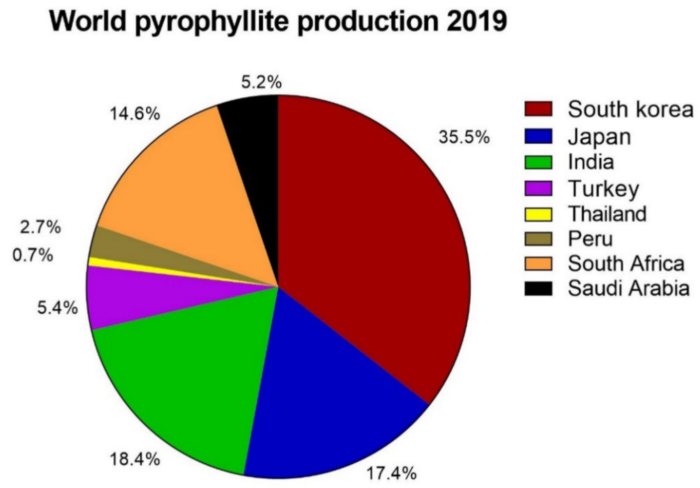

Figure1. The world pyrophyllite production in 2019 was 921.6 thousand metric tons. Data were extracted from USGS Minerals Yearbook 2019 (U.S. Geological Survey, 2020).

Pyrophyllite is a secondary mineral mostly derived from altered feldspar, containing silica (SiO_2) and alumina (Al_2O_3) as the main components and common impurities: Fe, TiO_2, CaO, MgO, and alkalis. Depending on its content of colored minerals, pyrophyllite occurs in all shades of color, especially light grey, white, greenish pink, yellow, brown, and green (Ambikadevi and Lalithambika, 2000). The grades and prices of pyrophyllite vary according to the alumina content and impurities. Impurities such as Fe and TiO_2 cause coloring problems for the final product and hinder its use in the industry, such as paper and ceramics. Highly pure pyrophyllite is rarely found naturally globally (Harvey and Murray,1997; Phillips and Powell, 2015). Hence, the industry tries to upgrade low-purity ores for use through physical and chemical treatment methods or a combination of both.

Pyrophyllite is a metamorphic mineral in its early stages and is very common, although it is rarely available as high-purity mineral samples. It is found as a component of schist, slate, phyllite, and other early-stage metamorphic rocks. This mineral is a phyllosilicate (also known as leaf silicate) with a sheet-like structure. The phyllosilicates are made of SiO4 tetrahedrons and create stacks of silicate layers. The sheets are not immediately connected to the following silicate sheets above or below. Two silicate layers are sandwiched between gibbsite layers in pyrophyllite, and the gibbsite is constituted of six hydroxides around octahedrally coordinated aluminum. The gibbsite layer (G) in pyrophyllite has the same structure as the gibbsite, but four oxygens have replaced four hydroxides from the silicate layers (S). Pyrophyllite's overall structure can be thought stacked S-G-S sandwiches (Das and Mohanty, 2009; Idiawati et al., 2017; Ravindra et al., 2016). In Saudi Arabia, pyrophyllite occurs mainly in the city of Yanbu in the Al-Madinah Al-Munawwarah province of western Saudi Arabia. The rock type is a metamorphic rock, and it is fine-grained, hard, compact, and massive. Moreover, it is highly foliated, crenulated, and mylonitized and displays schistose texture and banding, where some bands are rich in quartz and others rich in pyrophyllite. Due to the importance of pyrophyllite as an economical alternative to several minerals such as kaolin, talc, and feldspar in different industrial applications, there is an intention in Saudi Arabia to exploit pyrophyllite in the industry. Since there were no sufficient studies conducted to characterize pyrophyllite in Saudi Arabia, this paper aims to study the chemical and mineralogical characterization of Saudi pyrophyllite ore grades and propose its potential applications besides proposing beneficiation strategies for the low-grade one.

Materials and methods

Sample Collection, Preparation and Characterization

Two different grades of pyrophyllite ore were obtained from the SAMIROCK pyrophyllite mine (Yanbu, Saudi Arabia). The rocks were found as fine-grained, hard, compact, and massive. For the sample characterizations, different instruments were employed to perform the analysis. Transmitted light microscopy (ECLIPSE LV100DOL, Nikon) and reflected light microscopy were used for microscopic studies. In order to prepare the ore samples for microscopic studies, the samples were cut in random directions, and two samples were used to make two thin sections for examination by light microscopy. Furthermore, two polished sections were made for examination by reflected light microscopy. The remaining materials were prepared for further characterization, including chemical and mineralogical determinations. The remaining materials were ground in a laboratory ball mill using a roller machine (Sew-Eurodrive GmbH & Co KG, Germany) until size less than 80 μm. Then samples were obtained utilizing a mechanical riffle splitter (KHD Humboldt Wedag AG, Cologne, Germany). For chemical determinations, X-ray fluorescence (XRF) and field emission scanning electron microscope (FESEM) joined with an energy dispersive X-ray (EDX). XRF analyses of the samples were performed by mixing one gram of each sample with 6.0 g of lithium tetraborate beads to form glass beads. The glass beads were oxidized, melted, left to solidify in a casting mold, and then analyzed using XRF (Rigaku RIX 2000, Japan). For FESEM-EDX, the sample powders were placed on the carbon tape attached to the stub. Then the stub was placed in the sample chamber to be illuminated by an electron beam from FESEM (JSM-7600F, JEOL Ltd., Musashino, Akishima, Tokyo, Japan). Then EDX beam (EDX, Oxford Instruments, Abingdon, United Kingdom) was recorded the intensities peaks corresponding to each element at specific energy levels. For mineralogical, X-ray diffraction (XRD) and FESM were employed. XRD analysis was achieved using an X-ray diffractometer (Regaku, Ultima 1V, Japan) with analytical conditions of Cu kα radiation (40 kV, 40 mA), a step of 0.05◦, and scattering angle of 2θ in the range of 5◦ to 80◦. Meanwhile, FESEM (JSM-7600F, JEOL Ltd., Musashino, Akishima, Tokyo, Japan) was utilized for SEM images were taken at a low voltage of 5 kV to avoid overcharging the sample.

Results and Discussions

1. Microscopic studies results

The petrographical study of thin sections revealed that the rock is a metamorphic rock for both grades (A, B), and it is fine-grained, hard, compact, and massive. It is highly foliated, crenulated, and mylonitized and displays schistose texture and banding, where some bands are rich in quartz and others rich in pyrophyllite. The rock is composed mainly of pyrophyllite as major constituent associated with quartz and feldspars associated with rare amounts of muscovite, chlorite, impurities (opaque minerals), and sericite. Pyrophyllite occurs as fine-grained anhedral flakes arranged in parallel alignment with other constituents in the rock displaying schistose texture as shown in Figure 2a for grade A and Figure 2c for grade B. It sometimes warped around the group of crystals of quartz and feldspars to give an “Augen” texture (Figure 2a, c). Quartz occurs as fine-grained, anhedral strained crystals showing suture edges and wavy extinction, usually arranged in parallel alignment displaying schistose texture (Figure 2b, d). Feldspars is fine-grained; anhedral crystals intercalated with rock constituents and arranged in parallel alignment with other constituents to display the foliation texture. Muscovite is very fine-grained;

anhedral flakes that arranged in parallel alignment with other constituents to display the foliation texture. Feldspars is partially altered to chlorite, sericite, and clay minerals.

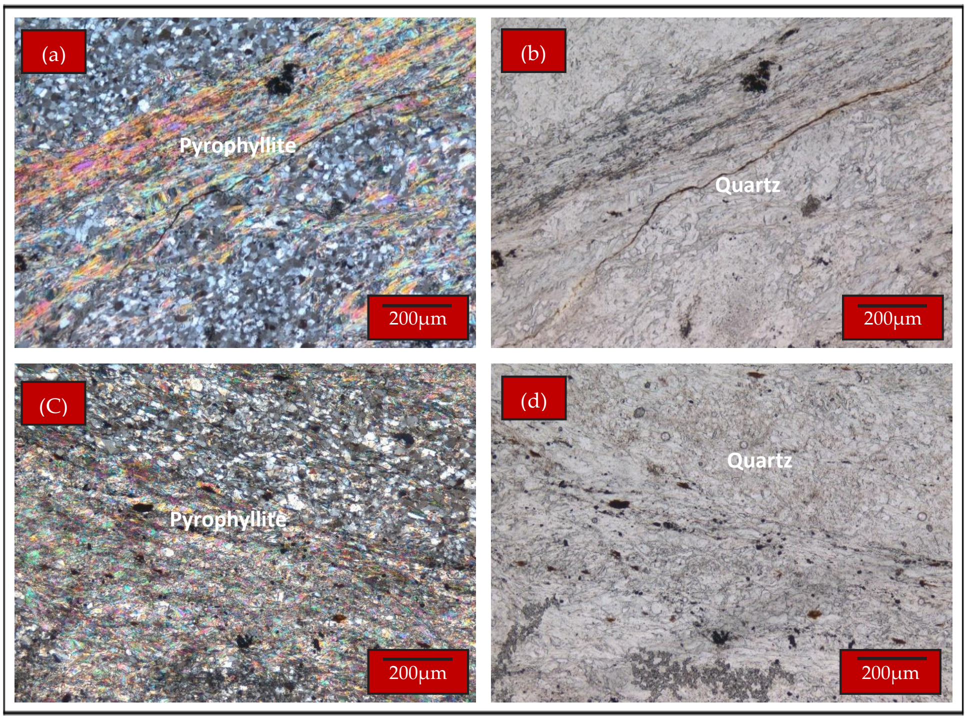

Figure 2. Photomicrographs of Saudi pyrophyllite grades: grade A (a, b); grade B (c, d)

The results of reflected light microscopy showed that the impurities are present in rare amounts and occur as very fine-grained, anhedral crystals disseminated in the rock following the foliation. Moreover, these impurities are evident in pyrite and hematite forms, which exist in pyrophyllite as oxide and sulfide minerals (Abdrakhimova ,2010; Bozkaya et al., 2007; Wiewióra et al. ,1993).The results also indicated that detected disseminated pyrite is noted altered to hematite in the rim and within pyrite. Figure 3 shows high pyrite reflectance, white-gray color, and dissolved at the rim and within it to hematite (brown color). The results showed that impurities in grade B were more noticeable than in grade A.

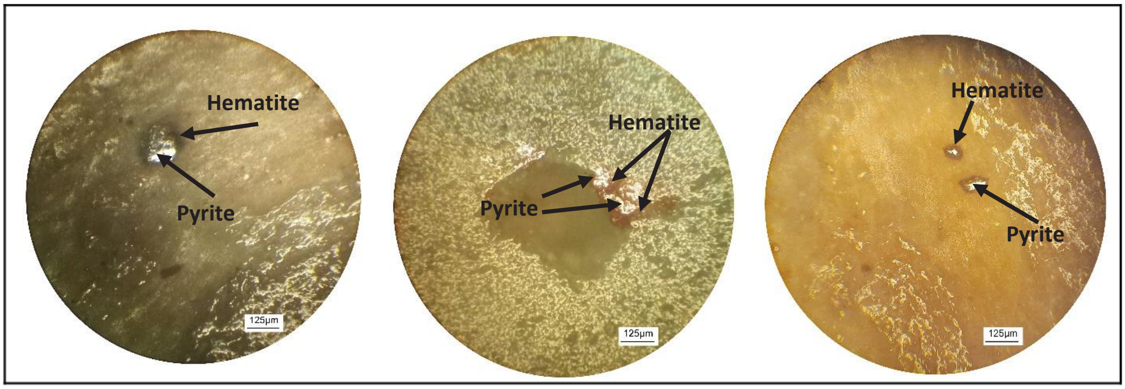

Figure 3. Photomicrographs of impurities in grade B, which are pyrite and hematite.

2. XRF and FESEM-EDX analysis

Table 2 and Figure 4 present the results of the XRF and FESEM-EDX characterization of the studied grades. The results indicate that Al_2O_3 and SiO_2 are the main components in both studied grades but differ in their contents (Table 2, Figure 4 c). The results also indicate that grade B contains Fe as an impurity element. The element patterns (i.e., Al, Si) shown in Figures 4a, b indicate the presence of Al_2O_3 and SiO_2, which are considered the main components of the pyrophyllite, and silicon (Si) also indicates quartz. Meanwhile, the potassium element (K) with aluminum (Al) and silicon (Si) suggests the presence of feldspar, muscovite, and sericite. The quality of pyrophyllite is determined by the content of Al_2O_3 and the content of impurities, especially Fe. Based on the content of Al_2O_3 and Fe, the grades of Saudi pyrophyllite ore can be classified into low-grade ore, which is represented by grade B, and high-grade ore, which is represented by grade A.

Table 2. Chemical compositions (wt.%) of Saudi pyrophyllite ore grades A and B measured by XRF spectrometry

Grade	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	CaO	Mg	P_2O_5	LOI	Total
Grade A	65.23	27.03	0.4	0.15	0.18	0.35	0.19	0.12	0.11	5.39	99.77
Grade B	68.12	24.05	2.06	0.17	0.14	0.55	0.64	0.14	0.13	3.6	99.60

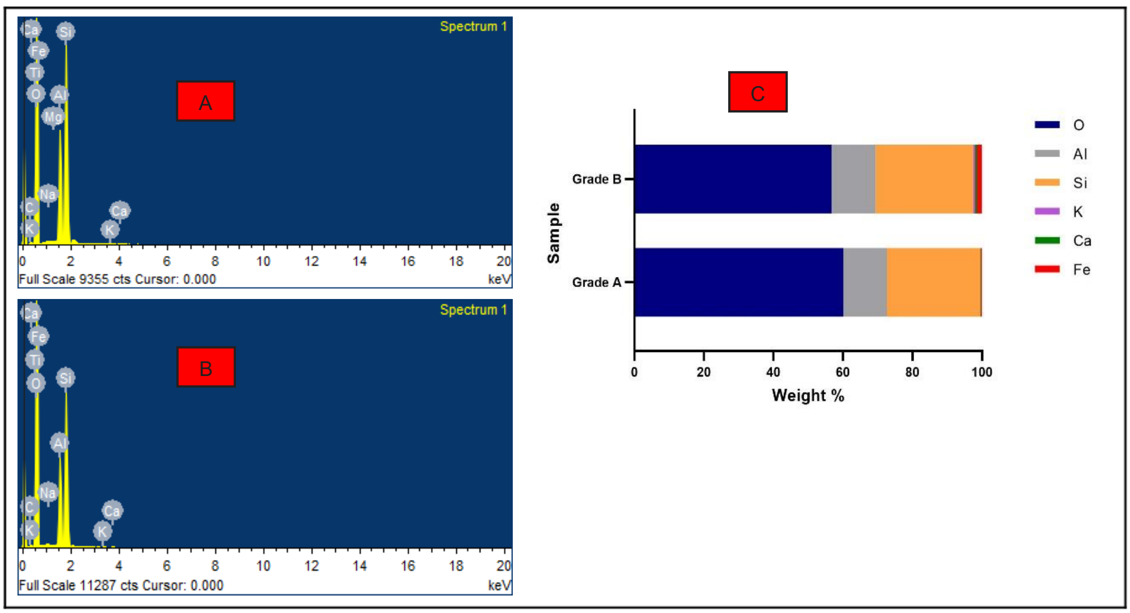

Figure 4. FESEM-EDX analysis of the studied grades: (a) EDX image of grade A, (b) EDX image of grade B, (c) elemental composition of grade A and grade B.

3. XRD and SEM analysis

The results of the mineralogy of the Saudi pyrophyllite ore grades are presented in Figure 5. The analysis of the XRD spectra of grade A and grade B showed that the predominant phase is pyrophyllite ($Al_2Si_4O_{10}(OH)_2$, card number: 01-071-1051) with quartz (SiO_2, card number: 01-089-6328) and feldspar ($KAlSi_3O_8$, card number: 01-089-6328) as main associated minerals as well as rare amounts of muscovite ($(KF)_2(Al_2O_3)_3(SiO_2)_6(H_2O)$, card number: 00-001-1098), which agrees well with the results of microscopic studies. The pyrite (FeS_2, card number: 00-001-1295) and hematite (Fe_2O_3, card number:00-001-1053) phases are observed for grade B (Figure 5b), which agrees well with the microscopic studies, XRF, and EDX results. This result can be attributed to the hydrothermal alteration that resulted in euhedral pyrite and hematite formation in the pyrophyllite.

The XRD spectra of the Saudi pyrophyllite ore grades (A, B) were separately compared. The results showed that the x-ray intensities of the pyrophyllite phase for grade A (Figure 5a) are higher than those of grade B (Figure 5b), which explains that grade A has a higher purity than grade B. Moreover, XRD spectra intensities of the quartz and feldspar for grade B (Figure 5b) are higher than those of grade A (Figure 5a), which explains that grade B has low purity compared to grade A. The results also indicated that the muscovite rarely appears in both grades (Figure 5a, b).

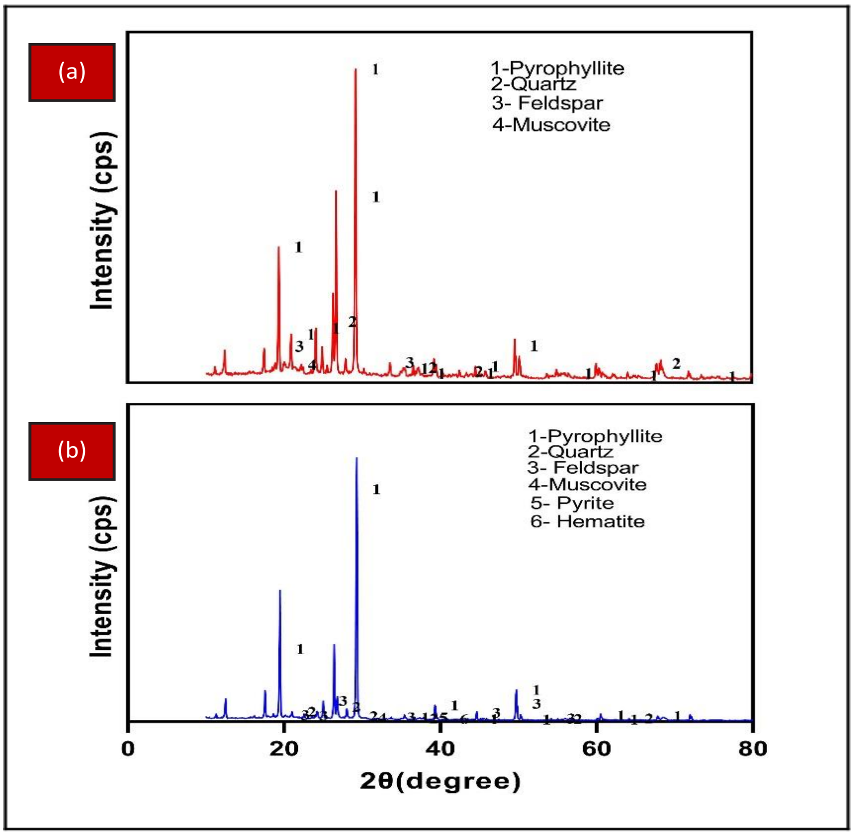

Figure 5. XRD results of Saudi pyrophyllite ore: (a) XRD results of grade A; (b) XRD results of grade B.

Figure 6 presents the results of the SEM micrographs of grades A and B at different magnifications. It displays a fine schistose texture for grade A (Figure 6 a, b, c) and grade B (Figure 6 d, e, f), which agrees well with the results of the microscopic study. It can be seen that pyrophyllite in the particles is highly foliated. Furthermore, the particles are fine and have anhedral flakes arranged, and the size is about 2–4 μm in width and 0.1 μm in thickness.

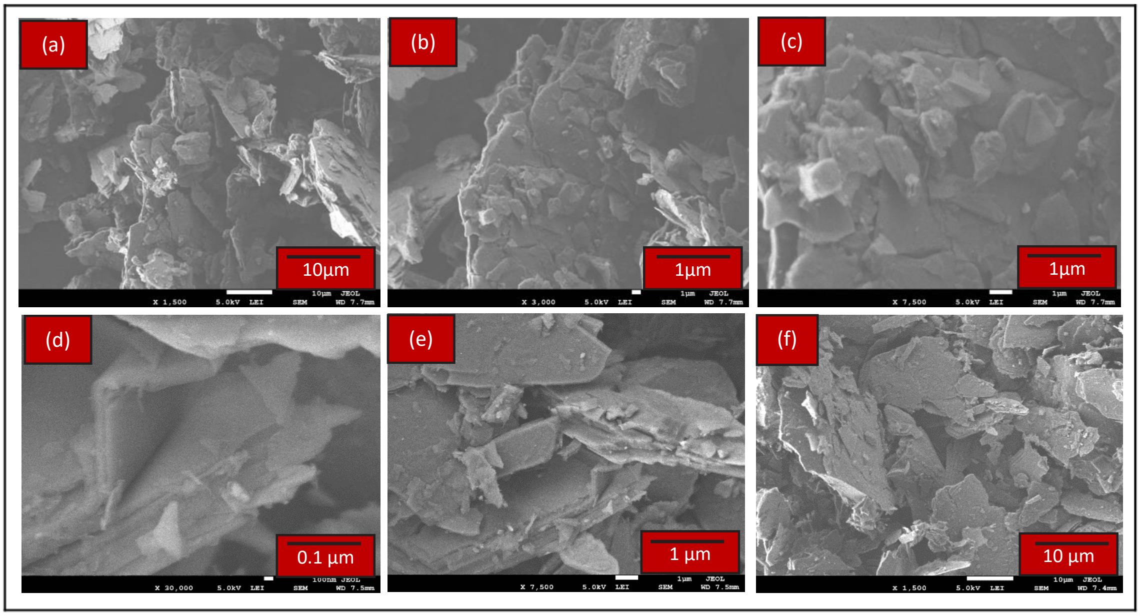

Figure 6. SEM images of Saudi pyrophyllite ore grades: Grade A ((a) x1500 (b)x3000, (c) x7500, 5 kV); grade B((d) x30,000 (e)×7500, (f) x1500, 5 kV).

Industrial evaluation of Saudi pyrophyllite ore

Several criteria govern using of pyrophyllite in industrial applications. The important criteria are the Al2O3 content of pyrophyllite and the percentage of impurities, especially the colored minerals (Ambikadevi and Lalithambika , 2000) . Table 2 presents the specification of different pyrophyllite grades. Investigated grades in this study mainly contain pyrophyllite as the main constituents associated with quartz, feldspar, and minor minerals such as coloring oxides. The schistose texture of Saudi pyrophyllite ore provides a platy structure beneficial for industry applications, especially when used as a filler in the paint industry. This platy structure increases resistance to film cracking, helps film dry, and promotes good dispersion (Wypych ,2021). Based on characterization results and specifications of pyrophyllite grades shown in table 2, potential applications of Saudi pyrophyllite ore grades can be suggested. Grade A can be used particularly in fillers, refractories, fiberglass, whiteware ceramics, white cement, and porcelain (Bentayeb et al. ,2003; Pradhan et al., 2015). It is also very suitable for cosmetics after prepared it and ensures that it has enough smoothness, softness, and whiteness. Grade A must be prepared to the required size and enhance the whiteness to comply with the specifications required for some applications. While grade B, due to its high iron content, its industrial applications are limited, therefore needs treatment to remove iron because of its adverse effect on the final products. Based on previous studies, upgrading methods for low-grade pyrophyllite ore vary depending on the characterization of ore and gangue minerals associated, including physical separation methods, chemical separation methods, and combined methods. The physical methods include magnetic separation, flotation, and Attrition-scrubbing. Magnetic separation removes ferro and paramagnetic iron-bearing minerals, whereas flotation and attrition-scrubbing increase alumina content and decrease silica content. For chemical treatment, leaching by oxalic acid and alumina is used to dissolve Fe. Combined methods such as magnetic separation and microwave roasting remove Fe and Ti from pyrophyllite ore (Abdrakhimova ,2010; Ali et al., 2021; Ambikadevi and Lalithambika, 2000; Bong et al.,2014; Bozkaya et al., 2007; Jena et al., 2015; Kim et al., 2019; Perepelitsyn et al., 2008). However, it can be used as a carrier for insecticides and as a dusting agent for the roofing and rubber industry where high purity is not required (Table 2).

Table 2. Different pyrophyllite grades specifications s

Pyrophyllite grades	Specifications	Ref.
Refractory grade	• Al_2O_3 18-21 % • Fe_2O_3 < 1%, TiO_2 1% Max • Alkalis 1% Max • Required size 150 - < 5 mm based on the type of product	(Jena et al. ,2015; Kogel et al., 2006; Pradhan et al., 2015; Shayakhmetov et al., 2018)
Ceramic grade	• Al_2O_3 15-19% • Fe_2O_3 1% Max, TiO_2 1% Max • Alkalis 1% Max • Required size -44 microns	(Jeong et al., 2017; Kizilkaya et al., 2016.; Kogel et al., 2006; Pradhan et al., 2015)
Fiber glass grade	• Al_2O_3 18-21 % • Fe_2O_3 < 0.5%, TiO_2 <1% • Alkalis 1% Max • Required size -45 microns	(ASTM ID: D5685-19., 2019; Bentayeb et al., 2003; Li, 2014; Pradhan et al., 2015)
Cosmetic grade	• Al_2O_3 <21% • Fe_2O_3 < 0.5%, TiO_2 < 0.5% • Alkalis 1% Max • Required size very fine (5 microns)	(Anja-Kostadinović et al., 2019; Chatterjee, 2009; Kogel et al., 2006)
Filler grade (Paper, plastic, paint)	• Al_2O_3 19 - 21% • Fe_2O_3 < 1.5% Max, TiO_2 < 1% • Alkalis < 1% • Whiteness >80 % • Required size -53 microns	(Chatterjee , 2009; Hubbe and Gill ,2004, 2016; Kogel et al. , 2006; MCHAFFIE et al., 1995; Ningbo Jiahe New Materials Technology Ltd, 2021; Pradhan et al., 2015; Vanderbilt Minerals LLC., 2013)
Carrier grade (Insecticides)	• Al_2O_3 19-21% • Fe_2O_3 1.5 % Max, TiO_2 < 1% • Alkalis < 0.5% • Required size -75 microns	(Belzunces et al., 2017; Indian bureau of mines, 2017; Indian Bureau of Mines, 2019; Indian Bureau of Mines, 2018)

For grade B, several treatment scenarios can be proposed based on the characterization results, which can be discussed as follows:

[1] *First scenario: High intensity Magnetic separation (Wet / dry)*

Due to the fact that disseminated pyrite in grade B is noted altered to hematite in the rim and within pyrite, high-intensity magnetic separation, whether wet or dry, can be tested and the separation efficiency measured (Liu et al. ,2013). After optimizing the crushing and grinding process to reduce the fines, several fractions can be tested and the separation efficiency measured for each (Figure 7).

[2] *Second scenario: Roasting and magnetic separation*

If the high-intensity magnetic separation process does not give satisfactory results, microwave roasting can be used before the magnetic separation process (Fig. 7). The change of phases during the roasting process into a more ferromagnetic mineral phase may give satisfactory results. The hematite phase at the pyrite's rim can be expected to change to the magnetite phase for grade B. Besides, pyrite may be changed into a more magnetic form such as pyrrhotite, improving the separation efficiency(Cho et al. ,2016; Kim et al.,2019).

[3] *Third scenario: Magnetic separation and flotation*

After the magnetic separation process, direct flotation can be utilized to increase the alumina content and reduce silica content. Direct flotation can be applied to the best products from the magnetic separation process to increase the quality (Figure 7).(Murat Erdemoğlu ,2016).

[4] *Fourth scenario: Roasting and leaching*

Oxalic acid is found to be effective in the dissolution of iron oxides from clay minerals, but in the case of pyrite, it is found to be ineffective (Cama and Ganor , 2015; Chandra and Gerson ,2010; mindat ,2011)temperature, organic acids, solution composition, and solution saturation state, as well as the solution ionic strength. Grade B with altered hematite, oxalic acid may effectively remove iron oxides after roasting (Figure 7).

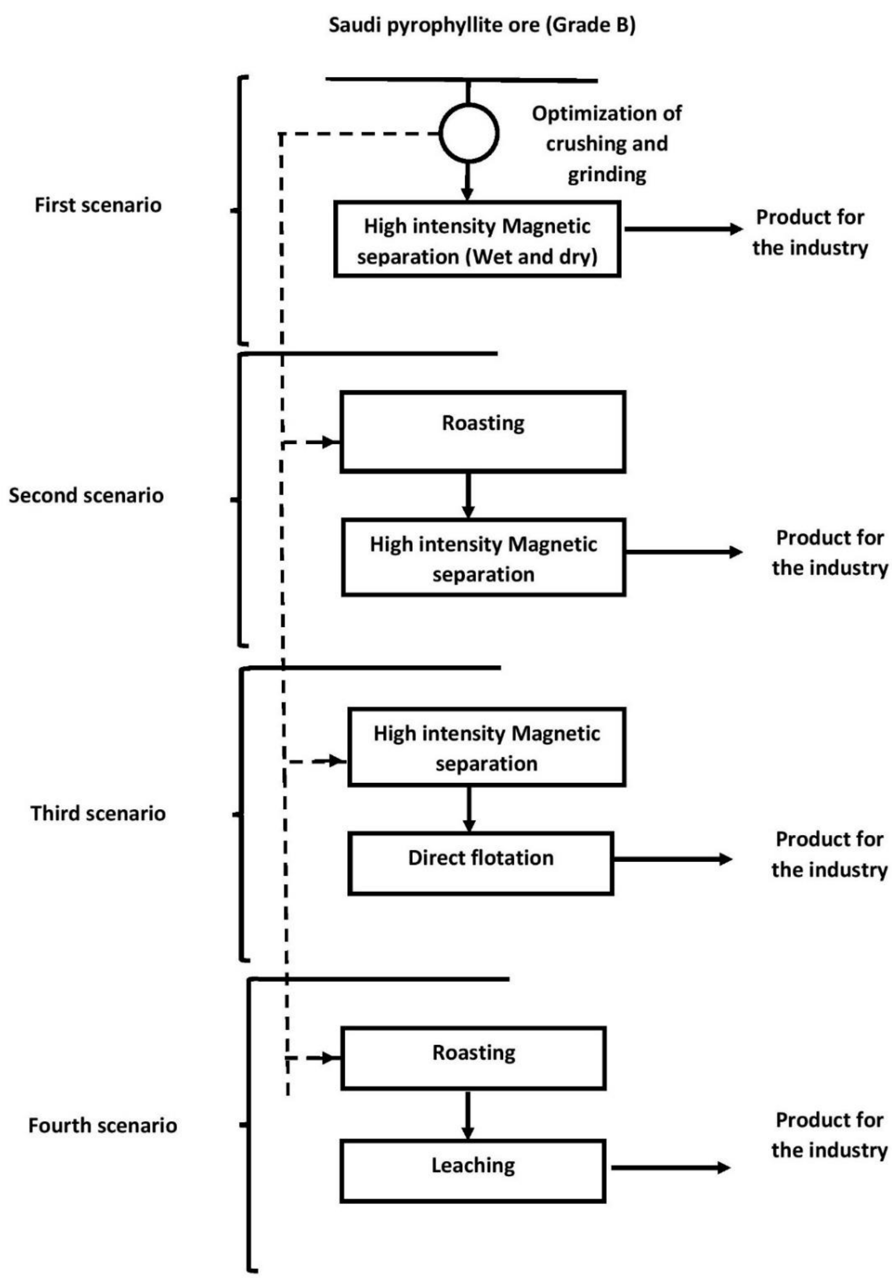

Figure 7. Proposed treatment scenarios for grade B

Conclusion

This study investigated the characterization and evaluation possibilities of Saudi pyrophyllite ore by different characterization methods. Key conclusions are summarized as follows:

1. The selected samples (labeled grade A and grade B) were characterized using microscopes, XRF, FESEM-EDX, XRD, and SEM studies.
2. The results of microscopic and XRD studies revealed that pyrophyllite is a major constituent associated with quartz and feldspars associated with rare amounts of muscovite, chlorite, impurities, and sericite. Furthermore, impurities are evident in the form of pyrite and hematite.
3. XRF and EDX analysis results have shown that grade A contains high alumina (27.03% Al_2O_3) and low iron (0.4% Fe_2O_3) Whereas, grade B contains a high iron content (2.06 % Fe_2O_3) and lower alumina (24.05 % Al_2O_3).
4. The SEM results confirmed that Saudi pyrophyllite ore has a schistose texture and is highly foliated.
5. Based on analytical results, grade A with high alumina content can be used directly in fillers, refractories, fiberglass, whiteware ceramics, white cement, porcelain, and cosmetic applications.
6. Results indicated that grade B needs to upgrade due to high iron content before being used in the industry.
7. Potential beneficiation approaches have been proposed for grade B based on characterization results.

Acknowledgments

Thanks go to all those who helped to improve this work, including those who participated and provided comments. Particular thanks go to the reviewers, whose comments improved this work.

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التوصيف الكيميائي والمعدني لخام البيروفيلايت السعودي وتطبيقاته المحتملة

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المُستَخلَص

تاريخ استلام البحث: 2021/12/15
تاريخ تعديل البحث: 2022/01/10
تاريخ قبول البحث: 2022/02/06

الهدف: نظراً لأهمية البيروفيلايت كبديل اقتصادي للعديد من المعادن مثل الكاولين والتلك والفلسبار في تطبيقات صناعية مختلفة، فهناك نية في المملكة العربية السعودية لاستغلال البيروفيلايت في الصناعة. ونظرًا لعدم وجود دراسات كافية تم إجراؤها لتوصيف البيروفيلايت في المملكة العربية السعودية ، تهدف هذه الورقة إلى دراسة التوصيف الكيميائي والمعدني لعيّنتين مختلفتين في الدرجة من خام البيروفيلايت السعودي واقتراح تطبيقاتها المحتملة إلى جانب اقتراح استراتيجيات إثراء للدرجة المنخفضة.

الطريقة: في هذه الدراسة ، تم توصيف عيّنتين مختلفتين في الدرجة من خام البيروفيلايت، من رواسب البيروفيلايت في غرب المملكة العربية السعودية ، لتطبيقاتهما المحتملة. تم استخدام الدراسات الميكروسكوبية، فلورية الأشعة السينية (XRF)، والمجهر الإلكتروني الماسح المرتبط بالأشعة السينية المشتتة للطاقة (SEM-EDX)، وحيود الأشعة السينية (XRD) للتوصيف الكيميائي والمعدني للعينات المدروسة.

النتائج: أظهرت نتائج المجهر والـ XRD أن عينات الخام الموصوفة بالدرجة A والدرجة B تتكون أساسًا من البيروفيلايت المرتبط بالكوارتز والفلسبار بالإضافة إلى كميات صغيرة من المسكوفيت والكلوريت والسيديريت كمعادن شائبة. كما أشارت النتائج إلى أن الشوائب عبارة عن معادن أكسيد وكبريتيد (هي البيريت، الهيماتيت). وفقًا لنتائج تحليل الـ XRF، تحتوي الدرجة A على ألومينا عالية (27.03% Al2O3) وحديد منخفض (0.4% Fe2O3) بينما، الدرجة B تحتوي على نسبة عالية من الحديد (2.06% Fe2O3) وألومينا أقل(24.05 % Al2O3). من المتوقع أن يتم استخدام الدرجة A التي تحتوي على نسبة عالية من الألومينا مباشرة في مواد الحشو والحراريات والألياف الزجاجية والسيراميك الأبيض والأسمنت الأبيض والبورسلين ومستحضرات التجميل. بالنسبة إلى الدرجة B، فإن محتوى الحديد العالي يحد من تطبيقاتها الصناعية. لذلك، يجب معالجته لإزالة الشوائب الحديدية قبل توريده إلى سوق البيروفيلايت.

الاستنتاج: بناءً على النتائج التحليلية، يمكن استخدام الدرجة A التي تحتوي على نسبة عالية من الألومينا مباشرةً في مواد الحشو والحراريات والألياف الزجاجية والسيراميك الأبيض والأسمنت الأبيض والبورسلين ومستحضرات التجميل. علاوة على ذلك، تحتاج الدرجة B إلى الترقية بسبب محتوى الحديد العالي قبل استخدامها في الصناعة.

مفاتيح الكلمات: معدن البيروفيلايت، منخفض الدرجة، التوصيف المعدني، التوصيف الكيميائي، التطبيقات الصناعية، طرق المعالجة.