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“A Review of Low-Grade Pyrophyllite ore Upgrading Techniques”

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Abstract:

Pyrophyllite ($Al_2Si_4O_{10}(OH)_2$) is a phyllosilicate often associated with quartz, mica, kaolin, epidote, and rutile minerals. In its pure state, pyrophyllite exhibits unique properties such as low thermal and electrical conductivity, high refractive behavior, low expansion coefficient, chemical inertness, and high resistance to corrosion by molten metals and gases. These properties make it desirable in different industries such as refractory, ceramic, fiberglass, cosmetic, paper, plastic, paint, pesticide, fertilizer, rubber, and roofing. Pyrophyllite can also serve as an economical alternative in many industrial applications to different minerals as kaolin, talc, and feldspar. To increase its market value, pyrophyllite must have high alumina (Al_2O_3) content, remain free of any impurities, and possess as much whiteness as possible. Since high-grade pyrophyllite ores are rare globally, low-quality ores need treatments to be suitable for industry. Several economic techniques have been used to upgrade low-grade pyrophyllite ores, including physical separation techniques, chemical separation techniques, and separation techniques that combine physical and chemical separation. These methods are used based on the characterization results of the pyrophyllite ore and the type of associated gangue minerals. Hence, this study aims to review the economic methods used to upgrade low-grade pyrophyllite ore and discuss its effectiveness besides classifying these methods based on the nature of gangue minerals associated with pyrophyllite.

Keywords: Pyrophyllite; Upgrading; Low- grade; Separation; Physical; Chemical

1.Introduction

Pyrophyllite (Al2Si4O10(OH)2) is a phyllosilicate mineral often associated with quartz, mica, kaolin, epidote, talc, feldspar, muscovite, siderite, and rutile (Abdrakhimova, 2010; Jeong et al., 2017; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006). When it is pure, it is desirable in the industry because of its distinctive properties (Bentayeb et al., 2003). It provides low thermal electrical conductivity; platy structure; low expansion coefficient; inertness; natural hydrophobicity; high refractive behavior; high corrosion resistance; and low hot-load deformation (Evans & Guggenheim, 2018; Zelazny & White, 2018). It is used in different industries such as ceramic, refractory, fiberglass, cosmetics, paper, plastic, pesticides, fertilizer, and roofing (Table 1) (Harben, 1994; Jena et al., 2015; Pradhan et al., 2015). Moreover, pyrophyllite may be an economical alternative to many minerals in industries due to its beneficial properties. For example, it can substitute for feldspar in the glass industry due to its naturally sufficient alumina (Al_2O_3) content and lower alkalis content(Das & Mohanty, 2009; Dolley, 2013). It may also substitute kaolinitic minerals in many industries such as ceramics and fillers because kaolin minerals are fast depleted and costly (Mukhopadhyay et al., 2010; Pérez-Maqueda et al., 2004). Since pyrophyllite is similar to talc in many physical properties, it can replace it in many industries, such as fillers. For its high safety compared to talc, it can replace it as a filler in the pharmaceutical application, and thus the problem of asbestos associated with talc can be overcome (Anja et al., 2019).

The quality and price of pyrophyllite depend mainly on the content of Al_2O_3 and impurities (Decleer, 1996). Therefore, pyrophyllite with high alumina content and low impurities is desirable in the industry. Impurities such as titanium(Ti) and iron(Fe) significantly influence the final product (Ambikadevi & Lalithambika, 2000). The presence of Fe and Ti leads to a change in the color of the final product (Harvey & Murray, 1997; Phillips & Powell, 2015). Furthermore, the presence of Fe affects the transparency of glass products, decreases the melting point of the refractory materials, and reduces transmission in optical fibers. Therefore, the percentage of Fe and Ti in pyrophyllite ore are determined according to the industry concerned (Table 2). For example, for the industry of refractory and paper, the ore must contain less than 1% Fe and Ti, as well as for the industry of pottery, tiles, and fillers, this percentage should not exceed 0.5% (Chatterjee, 2009; Mowla et al., 2008; Mukhopadhyay et al., 2010).

Table 1. Common pyrophyllite applications

Industry	Applications of pyrophyllite	Reference
Cosmetic industry	• The high purity powder is used as a cosmetic.	(Chatterjee, 2009; González-Miranda et al., 2018; Kairakbaev et al., 2021; Kurnia et al., 2020; Mukhopadhyay et al., 2010)
Fiber glass	• It is used as an alternative to feldspar in the glass industry as a source of aluminum. • Also it is used to prepare fiberglass batches.	(ASTM D5685-19, 2019; Elsandika et al., 2016; Li, 2014; Seo, Kim, et al., 2020)
Paper	• High purity finely ground is used as a filler in the paper industry and coating pigment	(Hubbe & Gill, 2016; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006; Song et al., 2020)
Plastic	• The medium purity is used as a filler material	(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.	("Canada: Trinity Resources – Pyrophyllite Pigments/Fillers," 2014; Erdemoğlu et al., 2004; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006; McGonigle & Ciullo, 1996)
Refractory	• It is used as 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 .	(R. Chen et al., 2017; Shayakhmetov et al., 2018; Shymanskaya et al., 2019; Truong et al., 2018)
Roofing	• The low purity is used as a dusting agent in roofing materials.	(Y. Chen et al., 2020)
Fertilizer	• The low purity is used as a soil conditioner and as a fertilizer carrier.	(Adamović et al., 2020; 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)
Insecticide	• The low purity is used as a filler and as a carrier material in insecticide.	(Belzunces et al., 2017; Hasanbegović et al., 2021; Indian Bureau of Mines, 2019; INDIAN BUREAU OF MINES, 2017; Pradhan et al., 2015; Reviews, 2018)
Others	• It is used as ornamental stone • It 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)

Table 2. Impurities limit for pyrophyllite to be used in different industrial applications.

Pyrophyllite grades	Impurities limit	Reference
Refractory grade	• Fe_2O_3 < 1%, TiO_2 1% Max	(Jena et al., 2015; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006; Pradhan et al., 2015; Shayakhmetov et al., 2018)
Ceramic grade	• Fe_2O_3 1% Max, TiO_2 1% Max	(Jeong et al., 2017; Kizilkaya et al., 2016; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006; Pradhan et al., 2015)
Fiber glass grade	• Fe_2O_3 < 0.5%, TiO_2 <1%	(ASTM D5685-19, 2019; Bentayeb et al., 2003; Li, 2014; Pradhan et al., 2015)
Cosmetic grade	• Fe_2O_3 < 0.5%, TiO_2 < 0.5%	(Anja Kostadinović, Milica Balaban, Adolfo Senatore, Maria Sarno, Claudia Cirillo, Pascale Massiani, Karima Baghdad, Franck Launay, Suzana Gotovac Atlagić, 2019; Chatterjee, 2009; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006)
Filler grade (Paper, plastic, paint)	• Fe_2O_3 < 1.5% Max, TiO_2 < 1%	(Chatterjee, 2009; Hubbe & Gill, 2004, 2016; Kogel, J. E., Trivedi, N. C., Barker, J. M., & Krukowski, 2006; MCHAFFIE, I.W. & BUCKLEY, 1995; Ningbo Jiahe New Materials Technology Ltd, n.d.; Pradhan et al., 2015; Vanderbilt Minerals, 2013)
Carrier grade (Insecticides)	• Fe_2O_3 1.5 % Max, TiO_2 < 1%	(Belzunces et al., 2017; Indian Bureau of Mines, 2019; INDIAN BUREAU OF MINES, 2017; Reviews, 2018)

Pyrophyllite world production is documented and shown in the graph (Figure 1) (National Minerals Information Cente(US), 2020). High-grade pyrophyllite ores are rarely found naturally, and the industry's increased demand has led to their rapidly depleting (Evans & Guggenheim, 2018; Zelazny & White, 2018). Therefore, with large quantities of low-grade pyrophyllite ores, processing them and raising their quality to meet industry demand became necessary. Low-grade pyrophyllite ore treatment aims to raise the alumina content and remove impurities, particularly Fe and Ti (Perepelitsyn et al., 2008). Based on previous studies, upgrading methods for low-grade pyrophyllite ores 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 is utilized to remove Fe, while flotation and attrition-scrubbing are used to increase Al_2O_3 content. For chemical treatment, leaching by oxalic acid and alumina is used for the dissolution of Fe. Combined methods, including magnetic separation and microwave roasting, are used to remove Fe and Ti. Under this background, this study aims to review the most important economic methods used for upgrading low-grade pyrophyllite ore and classify these methods based on the nature of gangue minerals associated with pyrophyllite (Abdrakhimova, 2010; Ambikadevi & Lalithambika, 2000; Bong Ju Kim, KangHee Cho, 2014; Bozkaya et al., 2007; Jena et al., 2015; B. J. Kim et al., 2019; Perepelitsyn et al., 2008).

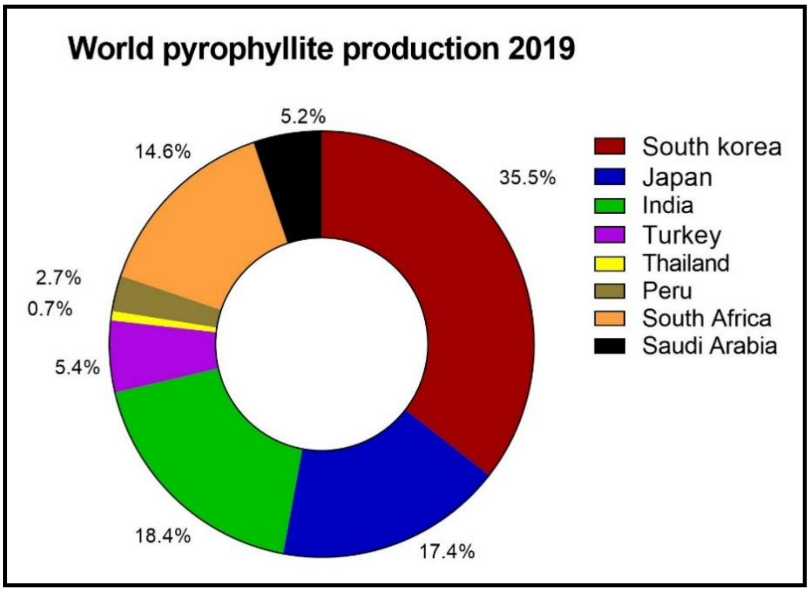

Figure1. The world pyrophyllite production in 2019 was 921.6 thousand metric tons. Data were extracted from USGS Minerals Yearbook 2019 (National Minerals Information Cente(US), 2020).

2.Upgrading of low grade pyrophyllite ore

Since pyrophyllite is desirable in industry and may be an economical alternative to many minerals, high-quality ores are rare globally, so with abundant quantities of low-quality ores, it should be processed to cover the needs of the industry. Several techniques have been used to treat low-quality pyrophyllite ore and have proven their efficiency and economy. These techniques include physical separation techniques, chemical separation techniques, and separation techniques that combine physical and chemical separation. These techniques are used according to the characterization outcomes of the pyrophyllite ore and the type of associated gangue minerals. In this section, these techniques will be discussed according to the contributions of researchers and the most important results obtained.

2.1 Physical separation techniques

Physical separation techniques are considered one of the important mineral processing methods for their efficiency and economy. These methods aim to treat low-grade pyrophyllite ore to remove impurities, especially iron, and raise the grade of alumina in the ore. According to the literature review, physical separation methods used to improve the quality of low-grade pyrophyllite include magnetic separation (wet/dry), attrition-scrubbing, and flotation.

2.1.1 Magnetic separation

Magnetic separation is employed to remove iron from pyrophyllite due to its influences on the final product. High-intensity magnetic separation is used, either wet or dry. It is used with pyrophyllite ore that contains a high silica content and phases of hematite, pyrite, and magnetite (Table 3) (Andji et al., 2009; Ferreira, 2017). Several studies have demonstrated the efficiency of using magnetic separation in removing iron from low-grade pyrophyllite. In a study conducted by (K. Cho et al., 2015), it was proved that magnetic separation led to Fe removal by 97.6~98.8%. Another study concluded that magnetic separation with a density of 4000 gauss would remove iron from pyrophyllite at rates of up to 96% (C., 2016).

The most important variables considered in the magnetic separation process are the feed rate, feed% of solids, particle size, and magnetic intensity. When performing the magnetic separation process, it is necessary to be concerned about these variables to ensure the efficiency of the process (Lin et al., 2017).

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2.1.2 Attrition-scrubbing

The Attrition-scrubbing technique is a simple beneficiation process in which the mineral particle is scrubbed under a high-slurry-flow speed, which also allows the particles to be affected by each other. This attrition leads to friction and collisions between the particles themselves. The attrition cell walls, impellers, and deflectors cause scrubbing, abrasion, and particle disintegration. This technique has wide applications for removing clay minerals from low-grade ores and has proven to be efficient in enriching several mineral ores, such as uranium and sand (Jiang et al., 2009). Moreover, this technique was shown to effectively concentrate low-grade pyrophyllite ore by significantly increasing the Al_2O_3 content and decreasing the silica (SiO_2) content (A., 2014). In a study, the attrition-scrubbing method was used to upgrade pyrophyllite ore associated with quartz and kaolinite. The study showed a significant improvement in the Al_2O_3 grade, where a very high Al_2O_3 grade of 29.33% was obtained for the finest size (-75 microns) compared to 21% for the Al_2O_3 grade in the feed, alongside a decrease in SiO_2 content to 61%, indicating high purity rates for pyrophyllite. Further, this study indicated that the attrition-scrubbing technique is effective for separating quartz and kaolinite from pyrophyllite (Erdemoğlu, 2016). Figure 2 presents an XRD analysis showing that the pyrophyllite was concentrated at a size of 75 microns under attrition-scrubbing. The major crystalline phase was pyrophyllite, which was increased via scrubbing compared to raw pyrophyllite, in which quartz was a major phase. Attrition-scrubbing clearly gives excellent results in separating clay minerals associated with pyrophyllite, which in turn improves the processing economy and energy consumption at the level of industry.

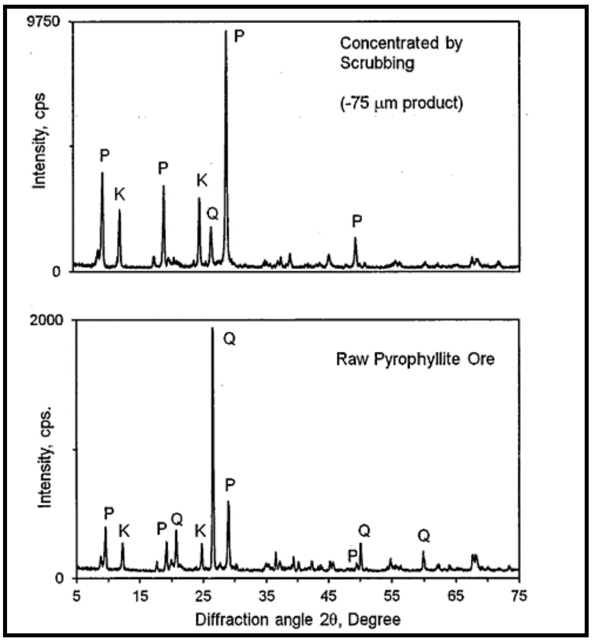

Figure 2. Comparison of the XRD patterns of raw pyrophyllite and selected pyrophyllite concentrates obtained by attrition-scrubbing. P: pyrophyllite; Q: quartz; K: kaolinite (Erdemoğlu, 2016).

2.1.3 Flotation

The main objective of enrichment by flotation is to recovery pyrophyllite from associated minerals, thus increasing the Al_2O_3 content and decreasing the SiO_2 content (K. Zhao, Wang, Wang, et al., 2019; K. Zhao, Wang, Yan, et al., 2019). Flotation is suitable for upgrading pyrophyllite when the main gangue minerals are quartz, feldspars, and kaolinite (Table 3). Several studies have found that pyrophyllite responds to cationic collectors because of its lower aluminum silica ratio, and its crystal structure contains the most cleavable planes. The most common flotation cationic collector for pyrophyllite is dodecylamine due to its satisfactory ability to collect aluminosilicate minerals at specific pH ranges. Flotation of pyrophyllite was studied using dodecylamine and found to give recovery of 96% of pyrophyllite(Das & Mohanty, 2009; Erdemoğlu & Sarikaya, 2002; S. M. Zhao et al., 2003). In a study, flotation was conducted for pyrophyllite, where the main associated minerals are quartz and feldspars, and the collector was dodecylamine. The study concluded that Al_2O_3 content increased from 26.2 to 29.5%, SiO2 content decreased from 63.62% to 55.71%, and the product's brightness was enhanced (Das & Mohanty, 2009). Furthermore, flotation of the pyrophyllite was carried out using 3- diaminoprpopane and N-dodecyl-1, where it was found that the recovery rate was higher than 80%. There are attempts to use the anionic collector in the flotation of pyrophyllite when the ore contains quartz as a gangue mineral. It was found that using sodium oleate (SO) as a collector would improve the efficiency of the flotation of pyrophyllite. Flotation of the pyrophyllite was also carried out using 3-diaminoprpopane and N-dodecyl-1, with a recovery rate higher than 80%. There were also attempts to use an anionic collector for the flotation of pyrophyllite ore containing quartz as a gangue mineral. It was found that using sodium oleate (SO) as a collector can improve the flotation efficiency of pyrophyllite (Seo, Choi, et al., 2020).

It should be highlighted that the hydrophobic surfaces of pyrophyllite serve as natural adsorption sites for non-polar organic molecules. As a result of its hydrophobicity, pyrophyllite can be easily separated from quartz and feldspar using collectorless flotation and a single type of frother. Based on this phenomenon, a study was conducted using a collectorless froth flotation to enrich pyrophyllite using Methyl Isobutyl Carbinol (MIBC) as a frother reagent. The associated minerals were quartz and kaolinite. The study concluded that using collectorless flotation to upgrade the pyrophyllite with different doses of MIBC produced an increase in Al_2O_3 content between 25% and 27% and decreased the SiO_2 content from 73.41% to 65.56% (Erdemoğlu, 2016). The XRD analysis in Figure 3 shows that the major crystalline phase was pyrophyllite, which increased via flotation with MIBC compared to raw pyrophyllite in which quartz was a major phase (Erdemoğlu, 2016).

In other cases, the flotation of pyrite from pyrophyllite was studied using N-dodecyl mercaptan as a collector along with a novel depressant (i.e., glucan) to achieve the selective flotation of pyrite and depress the pyrophyllite minerals. The studies demonstrated that a high recovery of Fe up to 98.51% could be obtained (K. Zhao, Gu, Yan, et al., 2019; K. Zhao, Wang, Wang, et al., 2019).

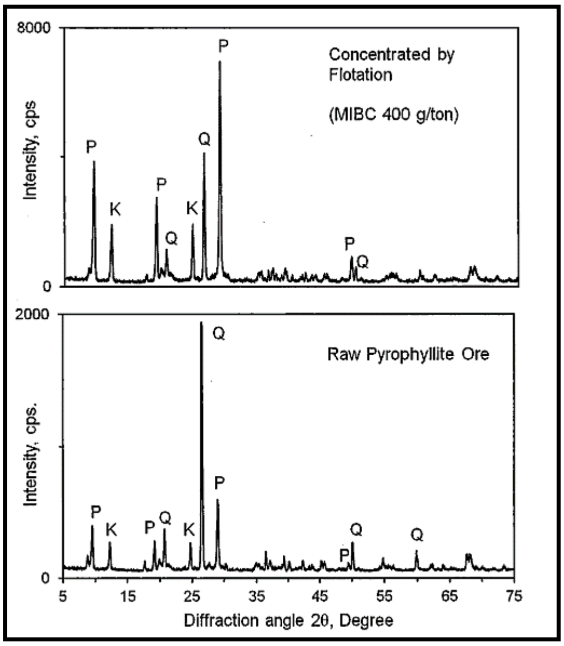

Figure 3. Comparison of the XRD patterns of raw pyrophyllite and the selected pyrophyllite concentrate obtained via collectorless froth flotation. P: pyrophyllite; Q: quartz; K: kaolinite (Erdemoğlu, 2016).

2.2 **Chemical separation techniques**

In some cases, chemical treatment is used when physical treatment does not remove iron contaminants effectively from low-grade pyrophyllite ore. Leaching is the most important chemical treatment process for clay minerals and can use either organic acids (e.g., citric acid and oxalic acid) or inorganic acids (e.g., hydrochloric acid, sulfuric acid, and sodium hypochlorite). However, there are limitations when using inorganic acids with clay minerals due to environmental pollution and the contamination of products with Cl and SO_4^{-2}. Therefore, organic acids are more widely used. Oxalic acid is preferred for dissolving iron contaminants in clay minerals because of its high leachability under different conditions (Kar et al., 2013; LEE et al., 1997). The effectiveness of oxalic acid in dissolving Fe from low-grade pyrophyllite ore to improve the quality of pyrophyllite was investigated in previous studies (Das, M., Chakrabarti S., Ghosh S., Ghatak T.K., and Mukhopadhaya, 2003; Jena et al., 2015; Zhang Jian, 2010). The critical parameters affecting the dissolution of Fe from pyrophyllite ore are the particle size, acid concentration, solid/liquid ratio, leaching time, temperature, and stirring speed. A study also conducted to remove iron from pyrophyllite using oxalic acid leaching. The main gangue minerals were quartz, muscovite, and orthoclase (Table 3). Fe, mostly goethite, was present as inclusions or intergranular spaces within the silicates. When oxalic acid was used to dissolve iron using a concentration of 0.3 M, a temperature of 90 °C, a pulp density of 5%, a particle size below 100 microns, and a leaching time of 60 minutes, it was able to remove up to 99.3% of the iron in the pyrophyllite (Jena et al., 2015). Oxalic acid is utilized with other chemical processes such as calcination, filtering, and drying to improve the quality of pyrophyllite by increasing its whiteness and brightness. These processes were applied to pyrophyllite micro powder with a particle size of 325-1200 meshes, and whiteness of greater than 87% was obtained (Das, M., Chakrabarti S., Ghosh S., Ghatak T.K., and Mukhopadhaya, 2003; Zhang Jian, 2010).

There were previous attempts to use ammonia as a solvent to improve the quality of low-grade pyrophyllite ore via the dissolution of iron because ammonia is characterized by a low rinsing cost, low toxicity, and high efficiency in separating iron components (B.-J. Kim et al., 2014). In a previous study, the effectiveness of using an ammonia solution to remove iron from pyrophyllite was further investigated. The associated gangue minerals were quartz and dickite, and euhedral cubic pyrites were also observed (Table 3). The effect of variables such as the ammonium sulfate amount, particle size, addition of hydrogen peroxide, and sulfuric acid concentration were investigated. The study concluded that iron removal using an ammonia leaching solution could be effective (B.-J. Kim et al., 2014).

2.3 Combined techniques

Chemical separation methods are often applied alongside physical separation methods to obtain a higher-purity product (Arslan, 2021). Recently, the efficiency of using microwave heating and magnetic separation in removing impurities (e.g., Fe and Ti) from pyrophyllite was investigated and considered a promising and environmentally friendly method for enriching low-grade pyrophyllite ore (K.-H. Cho et al., 2016). Through previous studies, the use of microwave roasting and magnetic separation removed up to 96% of pyrophyllite impurities based on operating variables such as irradiation time and magnetic field intensity (K.-H. Cho et al., 2016). An increase in impurity removal efficiency was caused by phase changes of the impurities, which became magnetized during microwave roasting. Additionally, the impurity-removal efficiency can be improved by adjusting the operating conditions related to roasting and magnetic separation. Another study confirmed that sequential microwave roasting and magnetic separation could remove Fe and Ti with high efficiency. Kaolinite, quartz, and dickite were the main gangue minerals, and impurities in pyrophyllite occurred in the form of oxide and sulfide minerals (Table 3). The study results indicated that Fe and Ti were removed from pyrophyllite with 86% and 68% efficiency, respectively, under 30 min of microwave irradiation and a magnetic field intensity of 2000 Gauss. Moreover, the study found that extending the microwave irradiation time and increasing the magnetic field intensity could improve impurity-removal efficiency, especially for paramagnetic Ti impurities (B. J. Kim et al., 2019). This method can effectively upgrade low-grade pyrophyllite ore and clay minerals, which can then be exploited after removing impurities. However, to use this technique in industry, more studies are needed to better optimize the mineral-phase changes to achieve effective separation and energy consumption.

Table 3 shows the appropriate upgrading method according to the gangue minerals associated with pyrophyllite and its effectiveness.

Table 3. Appropriate methods for upgrading low-grade pyrophyllite ore according to the associated gangue minerals.

Upgrading techniques	Gangue minerals associated with pyrophyllite	effectiveness	Reference
Magnetic separation (Dry /wet)	• High silicate content • Hematite, rutile, and pyrite	Magnetic separation effectively upgrades the low-grade pyrophyllite ore and offers high efficiency in removing Fe.	(C., 2016; K. Cho et al., 2015)
Attrition-scrubbing	• Quartz and kaolinite and clay minerals	Significant improvement in the Al_2O_3 grade; a very high Al_2O_3 grade obtains alongside decreases in SiO_2 content.	(Erdemoğlu, 2016)
Flotation	• Quartz, feldspars, and kaolinite	Flotation increases the Al_2O_3 content and reduces the SiO_2 content significantly.	(Das & Mohanty, 2009)

Leaching (Oxalic Acid / Ammonia solution)	• Quartz, muscovite, dickite , orthoclase , goethite , and pyrite	Highly efficient Fe removal.	(Jena et al., 2015; B.-J. Kim et al., 2014)
Sequential microwave roasting and magnetic separation	• Kaolinite, quartz, and dickite	This method is effective, promising, and environmentally friendly in upgrading low-grade pyrophyllite ore and removing impurities (i.e., Fe, Ti).	(B. J. Kim et al., 2019)

Conclusion

Pyrophyllite is a hydrated silicate mineral with unique properties that make it easily processable and suitable as a substitute for several clay minerals, such as kaolin, talc, and feldspar, in many industrial applications. The properties of pyrophyllite can be exploited to use the mineral as a refractory material in the refractory industry; as a raw material in the ceramic, fiberglass, and cosmetic industries; as a filler in the paper, plastic, paint, and pesticide industries; as a soil conditioner in the fertilizer industry; and as a dusting agent in the rubber and roofing industries. These industries require particular specifications of pyrophyllite to use the mineral, the most important of which is the grade of Al_2O_3 and the content of impurities. The grade of Al_2O_3 and the content of impurities determine the price of pyrophyllite, so obtaining high-alumina and low-impurity pyrophyllite is a goal for industrial applications. Since high-grade pyrophyllite is rare worldwide, low-grade pyrophyllite beneficiation is necessary to obtain a suitable product for industry. Upgrading methods for pyrophyllite aim to increase the alumina content and remove objectionable impurities (e.g., Fe and Ti). Techniques for improving low-grade pyrophyllite ore vary depending on the characterization outcomes and include physical separation techniques, chemical separation techniques, and separation techniques that combine the two. The most vital and efficient physical separation methods to remove impurities from low-grade pyrophyllite are magnetic separation, attrition-scrubbing, and flotation, mainly when the gangue minerals are quartz and clay minerals. Previous studies found that these physical techniques are more efficient and commercially viable for low-grade pyrophyllite ores. In terms of chemical methods, dissolution with oxalic acid works to remove iron efficiently and increase the degree of whiteness of the pyrophyllite when the process is carried out alongside other chemical processes, such as calcination. Finally, based on previous studies, it is clear that sequential microwave roasting with magnetic separation is a promising, environmentally friendly, and economical method for upgrading low-grade pyrophyllite ore and other clay minerals.

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