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Potential recovery of industrial minerals from granite waste as a circular economic opportunity to mitigate its impacts: an evaluative review

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Review scientific paper

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Abstract

Granite activity has a major contribution to the over-exploitation of natural resources, causing negative repercussions engendering an imbalanced ecosystem. In response to growing demand, there is an urgent need to optimise not only granite industry operations, but also related activities such as waste management in order to improve sustainability and strengthen the transition to a circular economy. Feldspar and biotite recovering, from the granite industry, offers an eco-friendly and economical solution, typically involving lower operating costs for mitigating both resources-depletion and waste impacts. As technology continues to advance, biotite and feldspar will play an increasingly important role in various sectors, including energy, construction, and industrial applications. Ongoing studies aim at improving the performance and sustainability of separation methods to obtain high-quality feldspars with low iron impurities. Besides flotation, gravity separation and leaching, magnetic separation remains an effective and eco-friendly method for extracting iron oxides imparting the ceramic quality, based on the selective adsorption of magnetic particles. Its application, in dry or wet mode, depends on various factors, such as chemical and mineralogical composition, grain size, and environmental constraints. The dry mode is often preferred for practical and ecological reasons, for producing high-grade concentrates materials for ceramic and others applications. Although, simultaneous recovery of both minerals is not discussed, literature provides physicochemical criteria influencing their response to separation techniques.

Keywords:
granite waste; feldspar; biotite; magnetic separation; mineral recovery

1. Introduction

The growing demand for raw materials, driven by global trends such as urbanisation and energy transition, highlights the urgent need to innovate in terms of resource efficiency, recycling, and circular economy practices in order to reduce the environmental impact and the dependence on primary mineral sources. To achieve this, it is necessary to optimise extractive activities, promote sustainable material use, and integrate secondary resources into supply chains, in line with circular economy strategies.

The granite cutting industry generates significant amounts of solid waste that is stockpiled in a large surface, due to the increase in global stone production caused by the continuous growth of construction activity; approximately 20–30% of the material is lost during the sawing and cutting of blocks, resulting in significant annual waste generation (**Mashaly et al., 2016**). Due to challenges in their proper management, processing plants frequently dispose of them in landfills. The reprocessing and recovery routes are definitely more beneficial than landfilling granite waste and exploiting resource usage. Thus, in an environmentally and economically advantageous context, studies focus in recycling granite waste as valuable materials with significant economic and environmental benefits. For instance, the study by **Alves (2015)** proposes two sustainable solutions to reduce waste management costs while creating materials with commercial value: the production of insulating fibers through verification and the recovery of steel shot through magnetic separation. In the environmental protection context, by recycling waste to clean up wastewater, granite waste has been used to synthesise nanofibers as a catalyst for removing hazardous dye pollutants from wastewater (**Lal Meena et al., 2023**). In addition, other studies deal with the recycling granite slurry from cutting, which enables the production of high-performance concrete with high mechanical and

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compressive strength, meeting the standards of the cementitious concrete market (**Mashaly et al., 2016; Ostrowski et al., 2020; Tangaramvong et al., 2021**). Given its high aluminosilicate mineral content, granite waste offers a valuable resource for geopolymer synthesis (**Nadeem et al., 2022; Hajiabadi et al., 2025**). Within the same framework of construction materials, the study of **C. Liu et al. (2025)** focuses on high-strength self-glazed glass-ceramics elaboration from granite sludge using intense sintering and glaze firing. In an alternative value-added context, the study by **Aquilano et al. (2025)** confirmed the presence of epidote enriched in rare earth elements, with particularly high concentrations (REE > 16% by weight) in granite waste. Although epidote remains underutilised for REE extraction due to a preference for other minerals, with the growing demand for critical raw materials, interest in alternative minerals containing REEs, such as granite, could intensify (**Vrbický and Přikryl, 2021**).

Granite waste has found widespread use in a vast array of applications where cost was a primary concern; however its most widely studied applications are in the ceramics and glass industries (**Pan et al., 2022; Lu et al., 2024; Zhou et al., 2024; C. Liu et al., 2025**) due to its high feldspar content, an important fluxing agent in ceramic body formulations, this material plays a crucial role in the ceramic manufacturing process. However, due to their varying sintering behaviour, impurity phases can cause surface imperfections. Biotite, one of the main phases alongside quartz, feldspar and other accessory minerals, makes up around 5% of the granite rock (**Chida et al., 2024**). It is among the primary impurities that must be removed prior to the sintering process in order to improve product quality and minimise economic and environmental drawbacks.

The purpose of any feldspar beneficiation process is to provide high-quality industrial feldspar product, specifically achieving a product with a high percentage of alkalis oxides (Na and K) and low percentage of iron oxides is recommended. Mainly gangue minerals associated to feldspar are quartz, and mica minerals one of the requirements of commercially ceramic industry is a reduced content of magnetic materials and iron bearing minerals such as biotite-mica which color-imparting and degrading the product quality. Previous studies aim to separate biotite from feldspar and quartz, although it is possible to extract usable concentrates of mica, feldspar, and quartz from granite, these three minerals are not all recoverable from the same source. Small-scale laboratory experiments have shown that feldspar and quartz can be recovered from some granite, while mica is obtained from others. Therefore, the objective of this study, designed as a literature review to address the identified research gap, is to explore strategies for jointly recovering all valuable products from the same sample of granite waste. Given the very similar properties of silicate minerals, which make their separation particularly challenging, the study's significance lies in proposing a multi-stage, cost-effective process that minimises material input while enabling the simultaneous recovery of industrial minerals and promoting environmentally sustainable recycling of granite waste. Quantitative cost data are not available within the scope of this study, but the emphasis is on the conceptual economic benefit of waste valorization and the recovery of granite waste as useful minerals.

2. Methods

The methodology adopted for this literature review is based on a comprehensive literature search conducted through the Web of Science scientific database aimed to sum up 102 articles from 16040 downloaded and published from 1986 to November 2025, exploring new proposals about biotite and feldspar separation. The information source (publication year, publication count, document type, countries/ regions of origin, and institutions) was documented. **Figures 1** and **2** respectively present the publication years and the leading countries or regions in terms of publication output. Among the countries and regions, China ranked the highest with 3741 publications, followed by the USA with 2617 and Australia with 1398. The target period covers the last ten years, from 2015 to 2025, in order to include the most recent advances. The "Analyse Results" and "citation report" features of the Web of Science online platform were employed to perform preliminary analyses. A total of 16040 indexed publications spanning the years 1986 to November 2025 were identified through the database query ("**biotite**" OR "**fedspar**" AND "**granite waste**" AND "**separation**"). The Filters applied: publication years 1986–2025, document type = article, language = English. Duplicate records were removed and merged using Zotero's built-in duplicate detection tool.

The selection process was conducted in several steps. After identification of records, duplicate entries were removed. The remaining studies (n=8090) were then screened on the basis of title and abstract to exclude clearly irrelevant publications (e.g., geology papers not addressing mineral separation). Potentially relevant articles were subsequently evaluated through full-text reading according to predefined inclusion and exclusion criteria. The inclusion criteria comprised peer-reviewed journal articles, written in English, and specifically addressing mineral separation techniques relevant to biotite and feldspar. The exclusion criteria included irrelevant research, non-scientific studies, abstracts without full text, and off-topic work and studies outside mineral separation (n=2819). Following this staged screening and eligibility assessment, 102 articles were selected for detailed analysis (see **Figure 3**). The selected articles were analysed according to several criteria: the type of technique used, the type of sample used, the main results, and the yields and contents obtained. An analysis

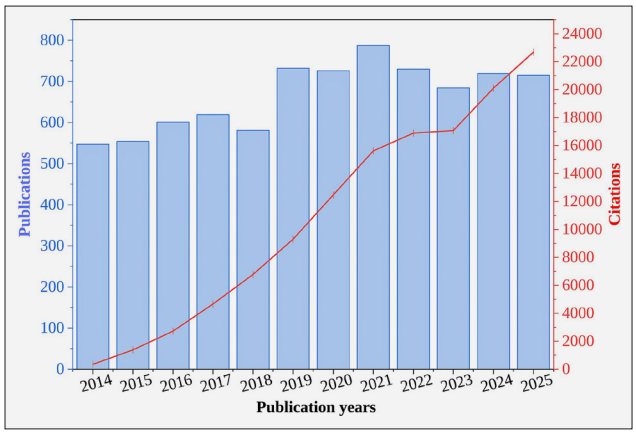


Figure 1: Times cited and publications in the last ten years (WoS core collection)

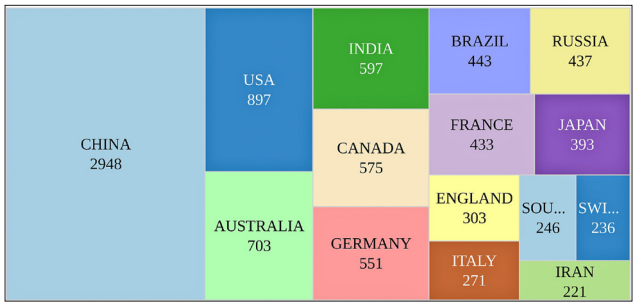


Figure 2: Treemap chart of Biotite AND feldspar AND granite waste by research area from the Web of Science Core Collection (WoS core collection)

grid was developed to compare the approaches, results, and gaps identified in existing studies. The results were organised around recurring themes such as magnetic separation, biotite separation, and combined methods, with an emphasis on the evolution of techniques, differences between studies, and future prospects.

3. Core literature review

Feldspar, an aluminosilicate mineral, is one of the main constituent in floor/wall tiles and in cement industry. Further, feldspar materials can be used in mechanical engineering as an abrasive, enamel frits, in the manufacturing of welding electrodes, and as a filler in various technological applications (**Terry, 1983; Zhang et al., 2018; Yassin et al., 2024**). Recent innovations in micro-nanostructural engineering and sintering techniques have led to feldspar-based ceramics with outstanding dielectric, mechanical, and thermal performance, including eco-friendly options derived from industrial waste (**Fuertes et al., 2022**). It plays an essential industrial role in the manufacturing of glass, ceramics industries, as a body constituent of glass (**Taylor and Brown, 1979**), as a fluxing agent in ceramics (**Sokolář et al., 2017**) and as a component of frit glazes (**Huang et al., 2021**).

Generally, ceramics are made up of 25-35 mass% feldspar, 15-25 mass% quartz and 30-50 mass% clay minerals (**Vasić et al., 2022**). The global consumption of feldspar is rising significantly by the increasing demand

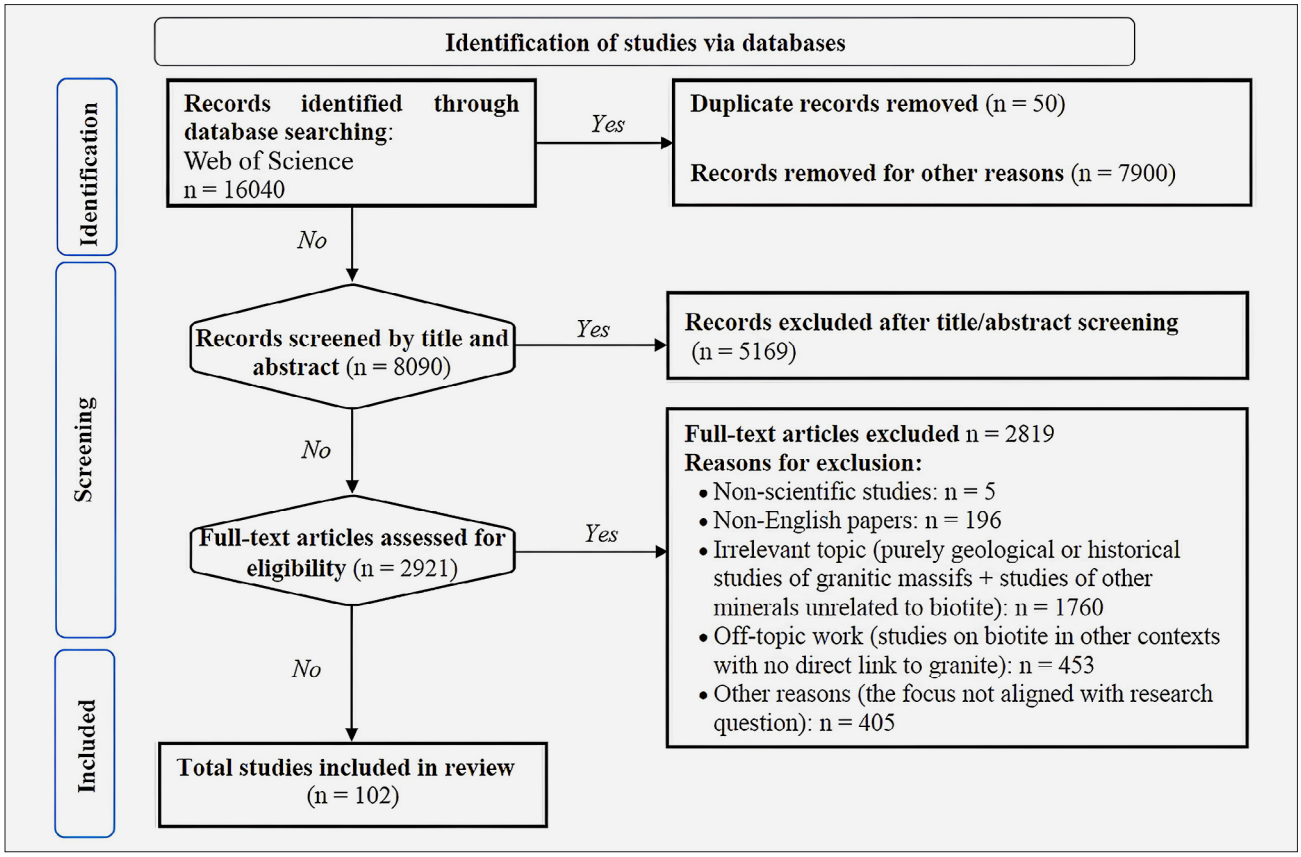


Figure 3: PRISMA-style flow diagram for research criteria analysis

of the glassmaking and ceramic industries (**Vasić et al., 2022**). Although widely distributed, pure feldspar is extremely rare, making high-quality products difficult to obtain. To meet this requirement, several processing methods have been developed, with flotation being the main technique for removing gangue minerals and recovering feldspar, using reagents such as cationic/anionic collectors, fluorhydric acid HF, and monovalent salts (**Zhang et al., 2018**). Other processes such as gravimetric and magnetic separation, selective grinding, and dissolved air flotation have also been explored (**Yassin et al., 2024**). It is well acknowledged that high-grade feldspar ought to not include more than 0.10% Fe_2O_3. The mandatory feldspar criteria impose the following contents SiO_2 <70%, Al_2O_3 >17%, Fe_2O_3 <0.1%, and K_2O and Na_2O >5%, industry requirements for the quality of feldspar materials are regulated. Flotation and leaching, although effective in removing impurities from feldspar, have significant environmental impacts. Magnetic separation, especially dry separation, is a more environmentally friendly alternative but is energy-intensive. Combining these methods would optimise feldspar processing while reducing its environmental impact (**Baila et al., 2024**). Consequently, as an ecofriendly alternative, the recovery of granite waste seems necessary as granite cutting and polishing waste contains a supply of feldspar and quartz materials which should be recovered to reduce the consumption of natural resources and mitigate the environmental depletion caused by their overexploitation.

Biotite, on the other hand, is a phyllosilicate mineral provides insightful clues about the nature and physicochemical parameters of its parent magma (**Abdel-Rahman, 1994; Martín-Hernández and Hirt, 2003**). The TiO_2, FeO, and MgO contents are crucial for accurately interpreting the absence or presence of biotite varieties, depending on their origin in granitic rocks: primary magmatic, re-equilibrated, or neoformed (**Nachit et al., 2005**). The economic importance of biotite lies in its technological properties which are essential for supporting various industrial applications, particularly in construction materials, paints, and plastics. In general, due to its non-toxicity, thermal stability, resistance to light and chemicals, and low density, mica is extensively employed as a high-temperature insulating material in various advanced industries, including nuclear, military, aerospace, and mechanical engineering (**Gerasimova et al., 2021**) (**Vachris, 1999; Sathyamoorthy et al., 2022; Dewangan et al., 2023**). It is also emerging as a promising solution to the challenges of flexible, heat-resistant dielectric materials, thanks to its flexibility, thermal stability up to 200°C, and high energy storage performance, meeting the growing requirements of flexible electronics and power devices (**Xu et al., 2018**). Biotite strongly concentrates certain transition metals necessary for energy transition, in addition to rare earth elements (**Laul and Lepel, 1987; Were and Keppler, 2021; Singh et al., 2021**). The combination of gravity and magnetic separation reveal significant potential for extracting critical raw materials (CRMs), particularly light rare earth elements, from paramagnetic fractions. Although the modest recovery rates, the contents of elements remain encouraging given the economic value that can be generated by their total recovery (**Aquilano et al., 2025**). It also finds applications in adsorption of radionucleide waste, biotite effectively sorbs cationic radionuclides through ion exchange. Its high sorption capacity and chemical stability makes it a potential candidate for radioactive waste geological disposal. Biotite acts as a natural barrier that can slow down or retain certain radioactive elements diffusion, helping to secure radioactive waste storage sites (**Bian et al., 2023; Cai et al., 2023; Chida et al., 2017; Iida et al., 2016; Fabritius et al., 2022; Chida et al., 2024**). Owing to its elastic and mechanical properties, biotite has a low tendency to crack, which enhances the stability of host materials considered for long-term storage of radioactive waste. Furthermore and in yet another field, biotite can be used in addressing potassium fertiliser shortages for sustainable agricultural development. It can serve as a soil amendment to improve soil quality and fertility, as it readily releases essential macronutrients such as potassium and magnesium vital for plant growth (**Baila et al., 2025**).

3.1. Understanding Biotite: Key features and separation significance

3.1.1. Magnetic behaviour

Biotite exhibits paramagnetic behaviour, induced by Fe^{2+} and Fe^{3+} ions. Unpaired 3d electrons from Fe^{2+} and Fe^{3+} ions create magnetic moments that temporarily align within the crystal lattice under an external field, giving biotite a magnetic response, but due to weak coupling and lack of long-range order, this alignment disappears once the field is removed. The presence of iron ions in biotite plays a key role in its paramagnetic behaviour. Besides, biotite displays characteristics of field-dependent magnetism. Its magnetic susceptibility is direction-dependent; it is generally higher within the cleavage plane (c-plane) and lower perpendicular to it, due to the layered structure of the mineral (**Beausoleil et al., 1983; Dunlop et al., 2006**). This configuration makes biotite easily magnetizable in the plane of its sheets, but much less so in the perpendicular direction along the c-axis. Measurements by **Martín-Hernández and Hirt, (2003)** confirm this trend; biotite's magnetic susceptibility ellipsoid is oblate, indicating maximum susceptibility in the basal plane and minimum along the vertical axis. Despite this marked anisotropy, biotite remains almost isotropic within its basal plane, meaning that it reacts homogeneously to the magnetic field regardless of horizontal orientation. Indeed, the {001} plane is the direction where the structure is most open and least dense with strong bonds. Layers of atoms are

linked by relatively weak forces, mainly Van der Waals bonds, in contrast to the perpendicular directions where atoms are more rigorously interlocked. As a result, iron ions (Fe^{2+}, Fe^{3+}) located in octahedral layers can more freely orient their magnetic moments in the {001} plane when a field is applied. This favors a stronger magnetic response in this plane, hence the magnetic anisotropy observed.

Under the effect of an oxygen-rich atmosphere (e.g. during rapid cooling of the rock), the iron contained in biotite begins to oxidise, it changes chemical state from Fe^{2+} to Fe^{3+} and becomes unstable in the structure. To adapt to this oxidation, biotite loses hydrogen and potassium, and creates small holes in its crystal lattice. This facilitates the departure of iron from the biotite. Released iron recombines with oxygen around or inside biotite to form tiny grains of magnetite (Fe_3O_4), a stable, well-crystallised magnetic mineral (**Zapletal, 1990; Dunlop et al., 2006**).

Biotite undergoes several transformative reactions under oxidizing conditions that alter its structure and promote magnetite formation. Firstly, biotite undergoes oxidation under the effect of an oxygen-rich atmosphere, the oxybiotite reaction involves the loss of hydrogen atoms, converting Biotite-H to Biotite-Ox and increasing iron oxidation.

Minerals containing iron oxides often exhibit remanent magnetisation. This magnetisation can be more stabilised by the crystalline structure of minerals, helping to further maintain the magnetic orientation. Instead, in rocks devoid of iron oxides, magnetic susceptibility is essentially linked to the iron content of paramagnetic minerals, such as biotite, although they do not exhibit permanent magnetisation associated to iron oxides in where their dipole moments are random in the absence of an external magnetic field, a residual low susceptibility persists, attributed to the paramagnetic and ferro/ferrimagnetic properties of constituent minerals (**Svoboda, 2004; Darmane et al., 2009**). Unlike feldspar and quartz, biotites can exhibit stable hysteresis and remanence typical of Single-Domain and small Pseudo-Single-Domain magnetites within their crystal lattice (**Dunlop et al., 2006; Özdemir and Dunlop, 2006**). These properties require the application of a coercive magnetic field to eliminate remanent magnetisation, which can be exploited in magnetic separation operation.

Oxygen fugacity is a critical parameter in ceramic processing by influencing redox reactions, phase stability, and material properties. It affects the melting behaviour of refractory ceramics. During sintering, oxygen fugacity influences phase formation stability, especially in complex oxides with multiple oxidation states like Fe^{2+}/Fe^{3+}. It alters the redox state of elements such as iron, impacting colour, viscosity, and the glass transition temperature. Additionally, redox conditions during processing drive the microstructure formation by promoting or suppressing defects, thereby affecting mechanical strength, electrical conductivity, and optical performance (**Agca et al., 2020; Neuville and Cormier, 2025**). Parameters such as the iron fraction in the octahedral site and the aluminum content are used to estimate oxygen fugacity and thermodynamic conditions. These data are valuable for predicting the behaviour of biotite during separation and treatment processes, especially when its composition affects properties like density or chemical reactivity as is the case in ceramic sintering (**Li et al., 2020; Gion et al., 2022**).

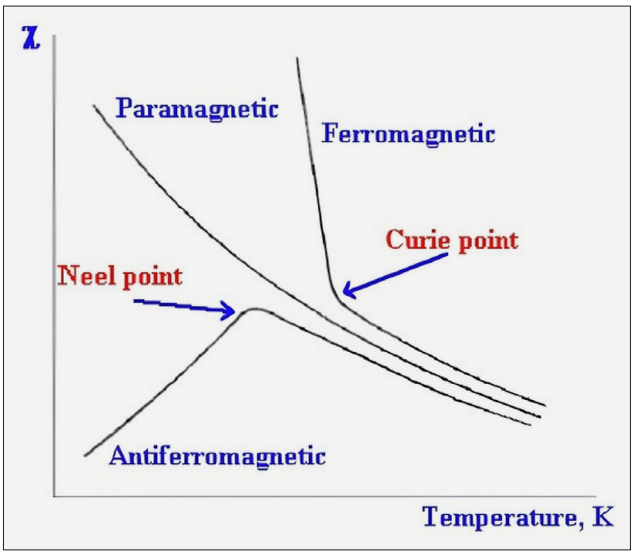


Figure 4: Magnetic materials behaviour depending on temperature (**Svoboda, 2004**)

3.1.2. Thermal behaviour

At high temperatures, biotite follows Curie–Weiss behaviour, typical of paramagnetic materials. However at very low temperatures, some iron-rich biotites may undergo antiferromagnetic transitions, where magnetic moments align in opposite directions between layers (**Beausoleil et al., 1983; Dunlop et al., 2006**). The study of the effective magnetic moment (P_{eff}) revealed the simultaneous presence of Fe^{2+} and Fe^{3+} ions in the system studied. Below 16 K, a strong internal field appears only for Fe^{3+} ions, suggesting that they become magnetically organised while Fe^{2+} remain isolated. The Fe^{3+} appear to interact antiferromagnetically, but the presence of Fe^{2+} impurities in their lattice could break this organisation, inducing ferrimagnetic behaviour. Thus, the Fe-mica compound exhibits two-dimensional ferrimagnetism with temperature-dependent magnetisation, particularly at low temperatures (**Takahashi et al., 1990**). When subjected to temperatures above the Neel temperature, ferrimagnetic and antiferromagnetic particles behave like paramagnetic particles, and the same is the case for ferromagnetic particles above the Curie temperature (see **Figure 4**).

Actually biotite increases the melting point. In ceramic processing, iron ions influence melting and thermal

behaviour through their variable oxidation states (Fe^{2+}/Fe^{3+}), which are modulated by oxygen fugacity. This mineral-forming parameter governs redox reactions and phase equilibrium, thereby affecting the melting points of iron-bearing phases. These variations impact the glass transition temperature, viscosity, and colouration of melts, highlighting the importance of precise control over iron content to optimise ceramic and glass manufacturing, enhance thermal stability, and reduce energy consumption (**Agca et al., 2020; Li et al., 2020; Neuville and Cormier, 2025**). On the other hand, micaceous minerals compromise the performance of the final product. Micaceous minerals, can lead to surface imperfections and discolouration in ceramic products, attributed to their coarse grain size and iron content (**Cinar and Durgut, 2019**). Another interesting aspect of the ions present in biotite lies in its elastic and mechanical properties, which depend heavily on its chemical composition, particularly the iron (Fe) and magnesium (Mg) content, influencing the chemistry of the octahedral site of its crystal structure. The higher the iron concentration, the less elastically stable the crystal and the higher its anisotropy altering the mechanical properties, particularly the flexural strength of the resulting material (**Hanlon et al., 2023; Xingtao et al. 2023**).

In view of these features and to enable distinct applications, feldspar and quartz must be separated from biotite for their use in ceramic production industry, while biotite can be recovered for alternative purposes.

4. Discussion

4.1. Gravity separation

Mica biotite is described as a heavy mineral with a density higher than quartz, the most common rock-forming mineral, with a density of 2.65 g/cm3. Feldspar, in turn, is considered a light silicate mineral due to its relatively low density compared to mica. These minerals vary in grain shape and density, enabling the use of gravimetric separation to separate these minerals of different densities individually (**Al-Shamary and Tamar-Agha, 2019**). Quartz and feldspar are coexisting silicate minerals that share similar physical and chemical features, making their separation challenging. Nevertheless, this is deemed a non-issue in the context of ceramic manufacturing, where both quartz and feldspar are required. Conversely, biotite is difficult to separate from its altered varieties, which are often incorporated through kaolinisation, chloritisation, and iron/magnesium leaching under hydrothermal and oxidizing conditions. Due to its strong mineral associations and similar density, biotite is poorly liberated and resists traditional gravity separation methods (**Cheng et al., 2022**). This limitation, resulting from the very close densities of granite minerals, renders gravity separation particularly challenging even at coarse particle sizes. Consequently, more advanced alternative pathways underscoring the necessity of complementing conventional physical separation with chemical approaches must be used in order to address the specific constraints associated in such specific cases, such as the hydrometallurgical process in the study by **Baba et al. (2019)** which involves separating biotite from kaolinite using a 1.0 mol/L concentration of oxalic acid as the leaching medium at 75°C for 2h. Approximately 9 g/L of the biotite-rich kaolinite ore reacted, resulting in a yield of 92.0%. The remaining unreacted fraction was mainly composed of siliceous impurities and has a potential interest as a by-product for specific industrial applications.

4.2. Flotation separation

Pyrometallurgical and hydrometallurgical processes are energy-intensive and cost-intensive in terms of reagents and expenses, making froth flotation primarily exploited as a pre-treatment technique. Actually, flotation effectively concentrated mica from kaolinised granite containing quartz and feldspar, which were recovered in the by-product. Analysis of the concentrate obtained using 400 g/t of AERO 3030C cationic collector at pH= 3.26 displays a composition dominated by mica (≈55%), confirming the effectiveness of flotation in mica recovery (**Sekulić et al., 2019**). Additionally, a full flotation circuit using various reagents and grinding conditions was tested to remove ferromagnesian minerals from granite, as separation by a shaking table proved ineffective. This approach also sought to recover feldspar and quartz concentrates separately (**Yotsumoto et al., 1991**). Further studies conducted on synthesised mixtures to evaluate the effect of biotite separation by flotation have been reported. The reverse flotation of an artificial biotite/quartz mixture (1:1), using 120 g/t of polyoxirane as a biotite depressant, 60 g/t of octadecan-1-amine as a quartz collector, and 20 g/t of MIBC as a frother, achieved a biotite recovery of 98%. The adsorption of polyoxirane on quartz is independent of pH, whereas its adsorption on biotite increases with pH, leading to the formation of various complexes, including hydrogen bonds, partially covalent bonds, and other non-covalent interactions, while on quartz, only hydrogen-bonded complexes are observed (**Mweene and Khanal, 2025**). In the same way, micro-flotation tests showed a biotite recovery rate exceeding 90% using a mixture of sodium dodecyl sulfate (SDS) and dodecylamine (DDA) collectors (molar ratio 5:1, concentration 5×10^{-4} mol/L at an alkaline pH (10-11)), while the recovery rate of quartz remained below 10%. The high synergistic effect of the collector mixture facilitated adsorption at the interface. A thin, rigid layer first forms with DDA, which adsorbs onto biotite through electrostatic attraction and hydrogen bonding, followed by a compact multilayer film after the addition of SDS, which is co-adsorbed through interaction with DDA and electrostatic attraction with the metal ions in biotite (**Xu et al., 2023**). Pertaining to

the same context of mixed anionic/cationic collector system, the study of **Liu et al. (2023)** investigates the effect of metal ions on the separation efficiency of biotite by flotation using sodium oleate (NaOL) and dodecylamine (DDA), and the study shows that the addition of metal cations significantly improves the separation between biotite and quartz. Tests on individual minerals revealed that biotite recovery reached up to 96.41% with Mg^{2+}. Although tests on artificial mixtures confirmed the increment of the Gaudin selectivity index, thereby facilitating separation, the adsorption efficiency on real gangue mineral matrices remains to be confirmed. On the other hand, separating biotite and muscovite, two types of mica typically found in granite ores, remains quite difficult due to the similar characteristics of these two micas. The study examining the influence of a mixture of anionic (oleate) and cationic (amine) collectors on the flotation reveals that muscovite can be selectively floated from biotite using a combination of oleate and amine collectors under alkaline conditions, but only at very low amine concentrations. The more negative surface charge of muscovite enables it to be more responsive to collector adsorption, oleate alone fails to induce flotation, but it enhances the effect of amine. However, excessive quantities of amine or oleate reduce both the selectivity and efficiency of flotation (**Hanumantha Rao et al., 1990**).

4.3. Magnetic separation

Magnetic separation is widely recognised as an ecofriendly method for recovering iron oxides, relying on the selective affinity of magnetic materials on mineral surfaces. Its application, in both dry and wet modes, is influenced by mineral composition, liberation size, magnetic susceptibility, and environmental considerations. Dry magnetic separation is favored for purification, while wet methods produce fine, slurry-like magnetic concentrates. The magnetic separation of biotite is based on its magnetic susceptibility, which is exploited as a method of mineral processing. As an iron-rich mica, biotite exhibits paramagnetic behaviour weakly attracted to magnetic fields, unlike silicate minerals such as quartz and feldspar, which are diamagnetic (see **Table 1**). This technique is commonly used in kaolin processing, feldspar purification, and the reduction of ferrous impurities in non-metallic minerals. Its effectiveness depends on the composition of the biotite (Fe/Mg ratio) and its degree of alteration (chloritised biotite may behave differently). Granitic biotite exhibits significant variations in its Mg, Fe, and Al content (**Mokaddem et al., 2025**). These identified differences influence the density and magnetic properties of biotite, which is crucial for physical separation techniques. Ferrous biotites are denser and could be better separated by gravimetry and magnetic separation, while magnesian biotites could respond differently to magnetic fields.

Table 1: Magnetic response of some granite minerals to magnetic intensity (**Rowson and Fears, 2021**)

Mineral	Magnetic intensity (Tesla)	references
Magnetite (reference mineral)	0.1 - 0.2	(**Rowson and Fears, 2021**)
Biotite	1.0 - 1.8	(**Rowson and Fears, 2021**)
Feldspar	Zero magnetic response	(**Rowson and Fears, 2021**)
Muscovite	1.6 - 2.4	(**Rowson and Fears, 2021**)
Quartz	Zero magnetic response	(**Rowson and Fears, 2021**)

Once captured, biotite particles maintain a constant speed equal to that of the conveyor belt, whereas unretained weakly magnetic particles accelerate due to the opposing forces action (**Xue et al., 2022**). Magnetic particles react exclusively to the magnetic field. Non-magnetic particles, on the other hand, are drawn into the process at field strengths below the sum of the opposing forces. At equilibrium, magnetic and non-magnetic particles, known as middlings, interact in a similar manner and contribute together to the separation process.

The selectivity of the separation process is therefore governed by the interplay of these multiple forces and is strongly influenced by the characteristics of the feed material characteristics, including its particle size distribution, magnetic susceptibility, and various physical and chemical properties, as well as by the processing parameters (**Yang et al., 2018**).

Studies listed in **Table 2** have demonstrated the effectiveness of magnetic separation achieving high iron content removal from granite/feldspar ores. The preference for dry high-intensity magnetic separation stems from factors like water availability, drying costs, consumer requirements, and sustainability, particularly for enriching paramagnetic iron ores based on differences in magnetic properties, particle size, density, and shape. The critical parameters to be adjusted are magnetic field intensity typically greater than 1 Tesla, slurry density, controlled flow rate, and separator geometry adapted to maximise residence time and recovery. Biotite is attracted to the magnetic pole, while the non-magnetic constitute from feldspar/quartz is removed and can undergo further processing. Wet operation improves selectivity and recovery.

The comparative analysis presented in **Table 2** from the literature highlight the main characteristics of different magnetic separation techniques, based on several technical criteria. The strength of the magnetic field varies considerably depending on the equipment ranging from 0.2 T to 1.96 T for dry systems, high-intensity wet separators (WHIMS) reach up to 1.4 T, offering greater selectivity, while rare earth magnet rollers and Frantz-type dry devices can reach 1.8 T, or even 1.96 T for some laboratory devices with induced fields, such as the MLH.

Table 2: Magnetic separation conditions for several feldspar/biotite samples

References	Sample type	Separator type	Magnetic field intensity	Particle size	Feed rate	Roll / belt velocity	Roll dimension	Splitter inclination	Thickness of the belt
(**Khalifa et al., 2023**)	(microcline/orthoclase), quartz, and plagioclase	Dry high-intensity magnetic separator Induced roll Lift-Type laboratory Model MLH-13-111-5)	1.96 T	45 µm to 2000 µm	3.5 g/min	0 to 100 rpm	127 mm × 50.8 mm	90°	-
(**Cinar and Durgut, 2019**)	muscovite, albite, microcline, montmorillonite quartz and biotite	Dry high-intensity magnetic roll separator	1.8 T	150 µm to 2000 µm	-	100 to 400 rpm	-		500µm
(**Hassan et al., 2017**)	albite, quartz, mica and muscovite	Dry high intensity rare earth magnetic roll separator	1.5 T	75 µm to 150 µm	120 g/min	72 rpm	-	76°	25µm
(**Celik et al., 2001**)	Albite, orthoclase, quartz, mica minerals	Rare-earth permanent magnetic roll separator (Permroll)	1.4 T	200 µm to 2000 µm	500 g	64 to 80 rpm	-	97°/62°	-
(**Gougazeh, 2022**)	K-feldspar, plagioclase; quartz. biotite and muscovite	High intensity dry Frantz isodynamic magnetic separator	1.4 T	300 µm to 38 µm	-	200 rpm	-	-	-
(**Xue et al., 2022**)	Biotite, cordierite, cronstedtite, albite, quartz.	Dry magnetic separator (DMS) (three stage)	1.25 T	75 µm to 4750 µm	-	190 rpm	100 mm × 205 mm	-	800 µm
(**Xu et al., 2022**)	Feldspar, quartz, epidote and biotite	Dry vibrating high gradient magnetic separator D	0.4 to 1.0 T	106 µm 850 µm	-	29 rpm	D = 2 mm	-	-
(**Ibrahim et al., 2002**)	Perthitic orthoclase and albite augite, biotite and hornblend.	Dry Frantz isodynamic laboratory separator (Carpco" induced roll magnetic separator)	0.96T	25 µm to 125 µm	200 to 800g/min	0 to 100 rpm	127 mm × 50.8 mm	15° /5°	-
(**Moura et al., 2019**)	Alkali-feldspar, quartz, biotite.	Dry high-intensity rare-earth roll magnetic separator (thrre stage)	0.73 T	850 to 212 µm.	20kg/min	215 rpm	240 mm × 2 m		830µm
(**Saisinchai et al., 2015**)	Na-K feldspar, quartz; muscovite, biotite and garnet	Wet high intensity magnetic separator (WHIMS)	1.4 T	63 µm to 297 µm	-	-	-		-
(**Eddy et al., n.d.**)	feldspar and glass sand from waste granite fines	Wet magnetic separator	-	428 µm	-	-	914.4 mm × 1828.8 mm	triple drum units	-

These high levels enable the effective processing of weakly magnetic minerals. In terms of particle size, these techniques cover a wide range from 4.75 mm to less than 45 µm. Modern dry separators can process fine particles down to 45 µm, unlike high-gradient vibratory systems (≥106 µm) and WHIMS (≈ 63 µm). Wet separators generally perform better for the finest sizes. High-intensity dry roller models are commonly used for minerals such as feldspar and quartz, while high-intensity wet separators (WHIMS) are preferred for fine particles, particularly in high-tonnage industrial contexts. High-gradient or vibrating separators, on the other hand, are suitable for very fine and complex materials. The number of separation stages is also a determining factor in the quality of the process; single-stage circuits are common in laboratories, while industrial installations often incorporate two to three stages for progressive enrichment. The design of the equipment impacts separation quality, the higher the number of stages in the process, the higher the purity obtained, but this is accompanied by increased technical complexity. Some multi-drum wet separators are even designed for continuous processing. Parameters such as feed rate, separator inclination, and belt thickness greatly influence the accuracy and purity of the concentrates. These parameters, combined with specific equipment configurations, have a direct influence on selectivity, concentrate purity and operational complexity, underlining the importance of technology selection based on process requirements and the characteristics of the material to be treated.

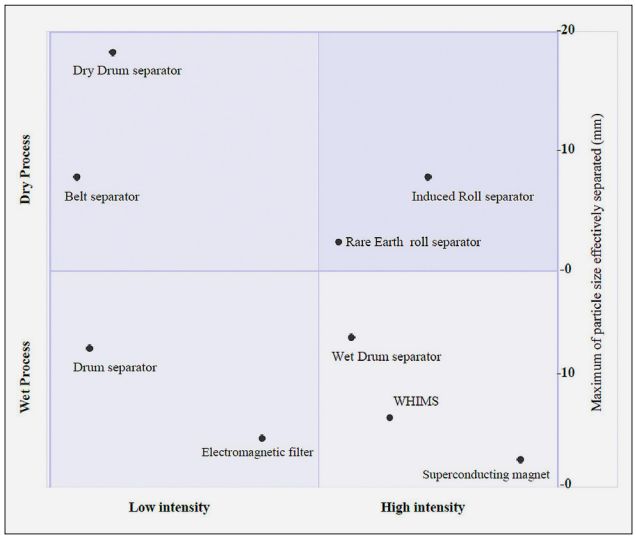


Figure 5: Magnetic separation techniques used to process ceramic raw materials (**Rowson and Fears, 2021**)

4.3.1. Influential factors of separation: equipment characteristics

The magnetic field strength generated by the magnetic separator fulfills a pivotal role in attracting and capturing magnetic particles. While the separation process itself is technically simple, the magnetic field's influence on particle trajectory and final position is substantial. Variations in separator design and field orientation result in lead to varied capture behaviours across equipment types. Initially developed using the dry process in the early 20th century, magnetic processing techniques underwent a major technological advance in the 1960s-1970s, with the introduction of high-intensity wet processes, enabling the efficient treatment of fine particles. It is distinguished by its low cost and ecological nature, being chemical-free method.

Magnetic separators have proven effective in extracting relatively larger mineral particles. Their design and functionality have seen notable innovations, leading to the emergence of diverse types of magnetic separation systems. Among these, dry and wet separators which can function under either low or high magnetic field strengths. Dry processing includes rare earth magnetic roller separators, induced magnetic roller separators, and rare earth roll separators; and wet processing, represented by high-intensity wet magnetic separators and electromagnetic filters. Selecting the appropriate type depends on various factors, chiefly the size and distribution of the feed material, its magnetic properties, and the desired processing capacity of the equipment (**Tripathy et al., 2017; Song et al., 2019; Zhang et al., 2020; Nzeh and Popoola, 2024**).

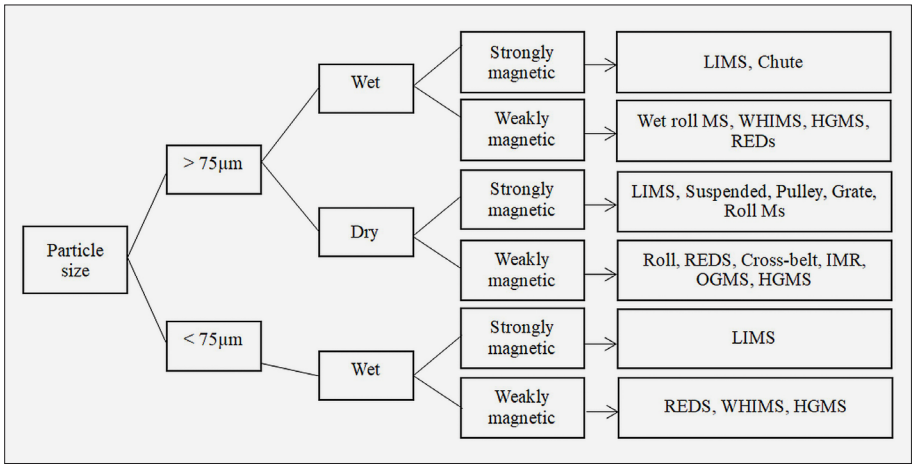


Figure 6: Types of magnetic separation process (**Svoboda, 2004**)

Three categories of magnetic separation are distinguished: Low-Intensity Magnetic Separation (LIMS), High-Intensity Magnetic Separation (HIMS), and High-Gradient Magnetic Separation (HGMS), which are offered through conventional and advanced technologies, enabling magnetic separation across fine to coarse particle sizes, while Wet High-Intensity Magnetic Separation is particularly effective for fine particles with low magnetic susceptibility, dry magnetic separators offer advantages in terms of energy efficiency and applicability to coarser fractions. The choice between these technologies is therefore strongly dependent on particle size distribution and operational context (see **Figures 5** and **6**). Only rare earth-based magnets can handle fine sizes in dry process (**Svoboda, 2004**).

Given that biotite is paramagnetic while feldspar and quartz are diamagnetic, their separation requires high-intensity magnetic technologies:

4.3.1.1. Conventional Technology of high intensity separators

– **Magnetic drum Separator**: The magnetic disc separator uses several high-intensity electromagnetic discs, arranged at different heights, to separate particles according to their magnetic susceptibility, from the most strongly attracted to the least sensitive. The intensity of each field can be individually adjusted, enabling targeted separation tailored to the characteristics of the materials being processed. Feed material is spread into a single layer on a vibrating plate and moves through rotating high-intensity magnetic disks. Magnetic particles are captured by high-gradient zones and carried to discharge chutes, while non-magnetic particles continue through the system and exit at the conveyor's end.

The lower particle size limit of conventional dry high-intensity magnetic separators imposes constraints on their utilisation with finer materials.

4.3.1.2. Advanced technology of high intensity separators

– **Electromagnet isodynamic Separator**: The "Frantz" type magnetic barrier separator is a dry magnetic separator designed for laboratory use. It features an electromagnet with adjustable intensity and operates with particles smaller than 500 microns. The device includes a feeder and an inclined chute, which guides the grains through the magnetic field. It employs a magnetic field generated by the electromagnet, combined with precisely shaped pole pieces, to concentrate paramagnetic particles at the centre of the field. This enables effective separation from non-magnetic or weakly magnetic materials, which are directed into separate containers. The system allows for highly sensitive separations based on subtle differences in magnetic susceptibility (**Bowman and Hnatyshin, 2022**).

– Induced Magnetic Roll Magnetic Separator (IMR): The induced magnetic roll separator (IMR) continuously extracts fine paramagnetic particles for mineral purification, particularly in the mineral and ceramics industries. The high magnetic field, generated by electromagnetism, attracts these particles to the surface of the roller, while non-magnetic particles follow a normal trajectory. The captured particles are then discharged at a point of lower magnetic intensity.

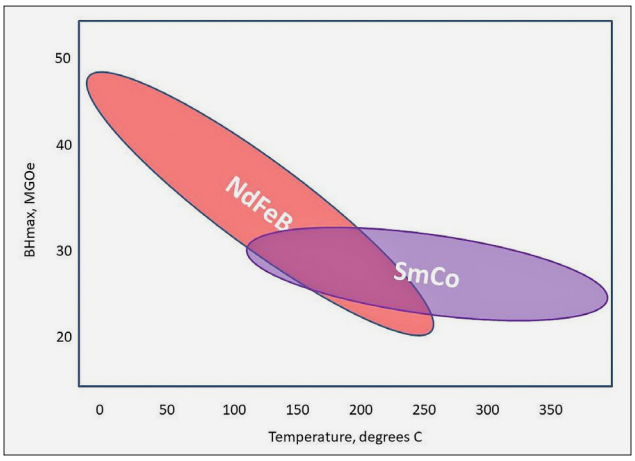


Figure 7: Temperature behaviour of NdFeB and SmCo magnets

– **Rare Earth Roll Magnetic Separator**: The Rare Earth Roll Magnetic Separator is a high-performance dry separation device designed to extract weakly magnetic minerals from process streams, especially when high product purity is required. It incorporates Neodymium-Iron-Boron permanent magnets within a composite high-intensity magnetic head pulley, constructed from thin magnetic discs interleaved with steel pole pieces that generate a powerful magnetic field exceeding 21,000 gauss. The roll is wrapped in a thin belt that conveys feed material into the magnetic zone. As particles enter the field, non-magnetic grains follow their natural trajectory and are discharged, while paramagnetic particles are attracted to the roll and diverted from the main stream. Due to the low static charge generated by the magnetic roller surface, the entrainment of fine particles is minimised, resulting in improved content and recovery of valuable minerals.

– **Cryogenic superconducting magnetic Separator**: High field induction is actually required to attract weakly magnetic colloidal and ultrafine particles, which pose a significant issue for the majority of conventional magnetic separators. The cryogenic superconducting high gradient magnetic separation technology shows promise in resolving this problem. When it comes to purifying fine feldspar particles thrown away as tailing from mafic minerals, this technique can produce encouraging results (**Kong et al., 2017**). In fact, the integration of high critical temperature superconductors, such as YBCO (yttrium barium copper oxide), marks a significant advancement in cryogenic magnetic separation, enabling the generation of powerful and stable magnetic fields comparable to those of permanent magnets. Un-

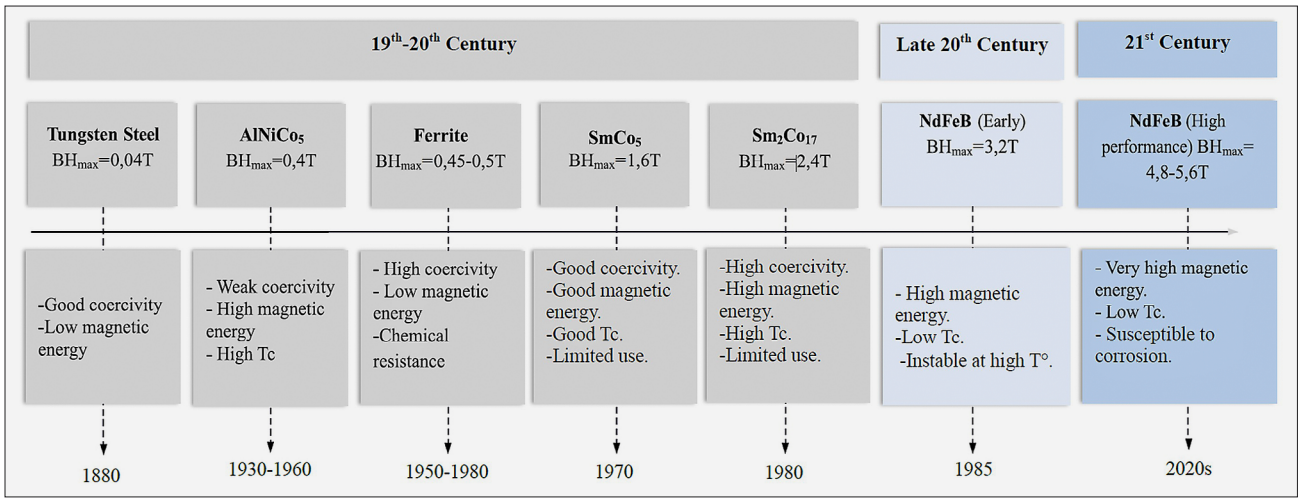


Figure 8: Advances in the development of permanent magnetic materials

like conventional magnetic separators, which are limited to a flux density of 2 T due to the saturation of ferromagnetic materials, superconducting systems can exceed 10 T, allowing for the efficient separation of magnetic, weakly magnetic, and even weakly fine-magnetic particles. Superconducting high gradient magnetic separators (HGMS) are typically designed with a magnetic matrix and are available in both dry and wet configurations. Dry HGMS systems have been studied since 1976, notably for coal desulfurisation and steel industry dust treatment, and have also proven effective in purifying potassium feldspar. The HGMS superconducting separator, with its intense magnetic field, is employed to remove heavy metal ions from wastewater in the steel industry (**Yang et al., 2017**), also to recycle iron ore residues in an environmentally-friendly way by extracting silica with a purity of up to 92.57%, paving the way for industrial uses or the production of high-quality silica (**Yang et al., 2018**). While its application in solid waste treatment remains limited (**Zhu et al., 2013**), wet HGMS systems dominate industrial applications due to their superior dispersion in pulps, though they require additional dehydration steps and are unsuitable for certain dry processes. Despite their advantages, superconducting HGMS technologies face some technical challenges such as remanence in the magnetic matrix and demand costly infrastructure to maintain magnet quality and stability (**Baila et al., 2024**).

– **Permanent magnets**: Permanent magnets consist of hard magnetic material, characterised by a remanent magnetic induction (Br) enabling them to generate a magnetic field effective for extracting paramagnetic minerals, including fine particles (<75 µm). They are used in particular for separating strongly magnetic materials and are made of ceramic alloys incorporating elements from the rare earth family, capable of producing a magnetic field of up to 1.5 T. In comparison, solenoids, designed for applications requiring a strong gradient or high magnetic field, can generate much higher forces (**Robert, 2020**).

– **Rare earth Permanent magnets**: The development of rare earth permanent magnets has led to the predominance of permanent magnetic separators, largely replacing electromagnet separators in the processing of magnetic minerals (**Chen and Xiong, 2015**). Their energy efficiency and ease of integration further enhance their appeal. Compared to traditional electromagnetic systems, they deliver superior performance at lower operating costs, making them essential in the mining industry despite the challenge of corrosion, which complicates maintenance. While primarily designed for dry environments, certain humid applications are also possible (**Tripathy et al., 2017**). Recent advances in the manufacture of permanent magnets have led to the emergence of new alloys, based on rare earth-cobalt or iron-neodymium-boron, offering very high BHmax and coercivity. They are cost-effective alternatives to traditional systems, thanks to lower investment and operating costs. These separators generate magnetic fields either through conventional electromagnets with resistive copper coils and soft iron cores, or via permanent magnets with high specific energy and strong resistance to demagnetisation (**Svoboda and Fujita, 2003**).

NdFeB magnets are very strong but heat-sensitive, SmCo magnets, on the other hand, are stable under heat with very little loss of BHmax (see **Figure 7**) but less powerful initially.

– **Rare earth Permanent magnets**: The development of permanent magnets has undergone several key stages, from the initial use of tungsten steel to the rise of neodymium-iron-boron (NdFeB) magnets. In the 1930s, AlNiCo alloys (aluminum, nickel, cobalt) marked a breakthrough with improved energy performance and good heat resistance, but their low coercivity and fragility limited their use. By the 1950s, ferrite magnets, which were less expensive, more resistant to demagnetisation, and chemically stable, had partially replaced Alnico magnets, despite their lower energy. The 1960s saw the arrival of samarium-cobalt (SmCo) magnets, offer-

ing high energy and excellent thermal stability, but their high cost slowed their adoption. Finally, neodymium-iron-boron (NdFeB) magnets, which appeared in the 1980s, revolutionised the market thanks to their power and competitive cost, although they are sensitive to corrosion and their Curie temperature is relatively low compared to SmCo magnets. Ongoing research is seeking to overcome the limitations of permanent magnets while identifying substitute materials to ensure their sustainability. The evolution of this technology should be based on the optimisation of NdFeB magnets, the development of rare earth-free solutions, and the integration of innovative manufacturing techniques.

The future of rare earth magnets looks promising across multiple sectors, with expanding applications. Advances aim to improve magnetic strength and efficiency, support renewable energy and storage solutions, enhance durability against wear and environmental factors, and reduce production costs to enable broader, more cost-effective use (see **Figure 8**).

4.3.2. Influential factors: Particle characteristic

According to **Equation 1**: $F_m = V \times \chi \times H \times \text{grad } H$ (where V denotes the particle volume, χ the magnetic susceptibility, H the magnetic induction, and grad H the magnetic field gradient), magnetic force depends on four main variables: particle volume, magnetic susceptibility, magnetic field strength, and field gradient. Given that the magnetic susceptibility of particles remains constant for a given mineral, adjustments to either the magnetic field intensity or particle size can be used to modify the magnetic force. The particle size distribution of biotite directly influences its behaviour during magnetic separation, due to mineralogical dissociation, force interactions, and process dynamics. Coarse biotite particles are poorly liberated, complicating their separation, whereas extremely fine ones tend to agglomerate with non-magnetic particles due to inter-particle interactions, and are disrupted by attractive forces such as Van Der Waals and electrostatic effects. . In contrast, intermediate-sized particles exhibit better dissociation and favorable dynamics, allowing for more efficient capture in the magnetic field. The competitive forces vary with particle size distribution: $F_g \approx rp^3$, $F_c \approx rp^3$ and $F_d \approx rp^1$ gravity (F_g), hydrodynamic drag force (F_d), and centrifugal force (F_c) are proportional to the particle radius. Thus, according to **Equation 1**, the effect of gravity and centrifugal force becomes dominant for larger particles. Conversely, in the Stokes flow regime, hydrodynamic drag predominates for finer particles. The finer the material, the higher the magnetic induction required, but the efficiency of recovery also depends strongly on the susceptibility of the matrix (**Chen and Xiong, 2015**). As reported (**Svoboda, 2004**), an equivalent magnetic force can arise from two antagonistic configurations: low particle size with high magnetic susceptibility and high particle size with low susceptibility. This reveals a compensated relationship between the two parameters, indicating that the magnetic force is based on their synergistic effect.

Granite's constituent minerals have distinct morphologies and cleavage properties. Biotite is characterised by an autogenous sheet structure and perfect cleavage. K-feldspar, with its double crystal lattice, and plagioclase, with its semi-autogenous plate form, have two well-developed cleavage systems. Conversely, quartz, with its prismatic morphology, has no cleavage planes (**Gao et al., 2021**). Grain shape is a main factor in magnetic separation; particles with irregular shapes tend to intensify magnetic fields at their corners and edges, promoting localised adhesion in these points. As a result, fine particles likely cluster together in the form of flocs, especially under wet low-intensity magnetic separation conditions (**Garcia-Martinez et al., 2004**). Additionally, analytical observations reveal a tendency for fine particles to adopt elongated shapes, with low aspect ratio, confirming their non-spherical shape, while coarser particles display more isometric shapes associated with higher aspect ratios. These morphological differences influence their magnetic response and aggregation tendencies (**Miceli et al., 2017**).

As clayey minerals interfere with the separation process, addressing ultrafine particles becomes a critical step in feldspar beneficiation processes to achieve selective separation, minimizing impediments to magnetic separation and mitigating the detrimental effects of particles cohesiveness which lowers the efficiency of dry magnetic separation. Accurately, the gangue material expected not hinders the movement of magnetic particles through inter-particle adhesion. Interactions between particles (F_a) are mainly governed by Van Der Waals forces (F_{wr}), electrostatic forces (F_{ek}), and liquid bridge forces (F_y). For dry powder particles in environments without an external electric field, the influence of electrostatic forces and liquid bridge forces is minimal compared to Van Der Waals forces. As particle size decreases, Van Der Waals attraction can exceed gravitational force (F_g), which can cause particles to agglomerate when they are close to each other. However, in pneumatic systems, the drag force due to air flow (F_d) generally dominates Van Der Waals forces, which helps prevent agglomeration and allows smaller particles to be handled. $F_m > F_d + F_c + F_g > F_a$. When dealing with ultrafine particles, most separation technologies struggle to generate sufficient magnetic force (F_m) against the total competitive forces ($F_d + F_g + F_c$), making it challenging to separate them (**Hu et al. 2024**). Intensifying the magnetic field to separate fine particles may seem beneficial, but it can actually reduce the selectivity of the process. A strong field attracts all particles in a similar manner. In addition, the magnetic susceptibility of minerals changes depending on the intensity of the field applied (**Hollingworth et al., 1984; Svoboda, 1994**). Hence, it is important to carefully control the operational parameters to achieve accurate separation. Performance may

be greatly enhanced by optimised feeding conditions, implementing equipment that delivers the feed in a less compacted and more dispersed state such as a vibrating feeder enhances particle mobility. Controlled flow rate increasing the interaction time between particles and the magnetic field, beneficially affect separation efficiency. Additionally, the desliming pre-treatment provides a purified surface to magnetic fields facilitating the deagglomeration of mineral particles before their introduction into the separator, and reducing interference from extremely fine gangue. Ultimately, improving separation clarity and selectivity. Various studies have described several methods for removing slimes from raw material (**Read et al., 1976; Malayoglu and Ozkan, 2019; Morkun et al., 2021**).

4.3.3. Influential factors: Operational parameters

In a magnetic separation system, the force of the fluid acts in opposition to the magnetic field. In a dry process, this opposition is reduced, which favors the attraction of magnetic particles, especially as they are not held back by the viscosity of the liquid. However, gravity has a greater influence on the trajectory. The dry magnetic separator offers good performance thanks to its extrusion structure, which creates an intense field and a strong induction gradient, facilitating the attraction of biotite particles. However, its efficiency decreases for very fine particles, which are often prone to aggregation due to magnetic interactions between biotite particles (**Xue et al., 2022**). Dry separation processes have largely been limited to treating materials coarser than 75 microns, which has excluded their application in processing ores with fine liberation characteristics, an area expected to gain importance in the future. As demand for low-grade minerals with fine-micron release properties increases, research will increasingly focus on fine particles (**Read et al., 1976**). Previous research has identified multiple factors influencing the efficiency of dry magnetic separation, such as roll diameter, magnetic field intensity, particle size, magnetic susceptibility, and magnetic field gradient. These parameters are subsequently linked to operational variables including magnet-to-steel ratio, belt thickness, number of separation stages, feed rate, and roll speed. Nonetheless, limited research has been conducted on capture dynamics and separation mechanisms within dry magnetic separators. In-depth studies on the dynamic capture behaviour of dry processes are needed to improve their efficiency and bridge current knowledge gaps (**Xue et al., 2022**). On the other hand, the wet process offers better dispersion of fine particles, exposing them more effectively to the magnetic field, which improves overall separation despite slightly attenuated attraction. The magnetic response in suspension is more dynamic than in a dry environment, as particles are not fixed. Within the fluid medium, ferromagnetic particles are more dispersed and move freely towards the high-field areas enabling their reorientation in response to external magnetic field, thereby promoting their alignment with the magnetic field direction. This dynamic behaviour also facilitates the formation of particle clusters, which collectively intensify the magnetic response. Each particle locally influences the magnetic field by attracting field lines, resulting in a concentrated magnetic flux in its vicinity. These combined effects contribute to a significant increase in the overall magnetisation. However, magnetic flocculation may promote the clustering of particles into complex structures that profoundly impact the behaviour of the fluid by altering the physical properties of the suspension, notably by increasing viscosity and accelerating sedimentation (**Stener, 2015**). In fact, the viscosity of magnetic suspensions is highly anisotropic, although it can be externally adjusted by varying the magnetic field, it is crucial to consider magnetic flocculation, as it can compromise the stability of the system (**Zipser et al., 2001**).

Magnetic separation has been applied in many investigations, independently or alongside with other supplementary techniques. It is frequently integrated into a full treatment circuit including flotation, gravimetric separation or chemical leaching, depending on the purity requirements. Actually, the distribution of iron and magnesium in biotite directly influences its density and magnetic susceptibility, two key parameters for gravimetric and magnetic separation. The combination of gravity and magnetic targeted magnetic separation of diamagnetic quartz and feldspar concentrates could also enable the production of valuable by-products representing an interesting commercial source. As some fractions contain grains composed of several minerals, it would be advisable to reduce the maximum particle size to optimise the separation (**Aquilano et al., 2025**). However, reducing grain size can hinder gravimetric separation essentially based on the particles weight and size. Therefore, the selective adsorption capacity of biotite for certain elements could be exploited in physicochemical separation processes, such as flotation, targeting the elements enriched in biotite (**Burat et al., 2006; Were and Keppler, 2021**). The study of **Ahmed et al. (2023)** employs a combination of high-intensity magnetic separation and flotation to purify feldspar by reducing the concentration of mafic minerals associated with biotite. Optimal conditions were achieved at a magnetic field intensity of 1.6 T, resulting in a feldspar concentrate containing 0.16% Fe_2O_3 (compared to 0.4% initially), 0.01% TiO_2, and 10.31% alkali oxides (K_2O + Na_2O), with a mass recovery rate of approximately 69.24%. As a result, the process demonstrated effective recovery with minimal impurity levels, and a final product compliant with the composition standards required for the production of white glaze and ceramics was obtained. In the same vein, through a combination of high-intensity dry magnetic separation and flotation applied to nepheline syenite ore, a 56.6% feldspar concentrate was separated from the biotite gangue, with enhanced alkali content and reduced iron and titanium impurities.

Table 3: Comparative efficiency of different separation methods

Technique	Effectiveness	Performance and Sustainability	References
Magnetic separation	Recovery: 85–95 (%) Purity : 85–90 (%)	Highly selective for magnetic minerals; low water consumption; compact design Ineffective for weakly magnetic minerals without activation; costly high-intensity magnets Minimal **environmental impact**, mainly related to energy use Relatively low cost	(**Khalifa et al., 2023**) (**Xue et al., 2022**) (**Ibrahim et al., 2002**)
Flotation	Recovery: 70–85 (%) Purity: 90–95(%)	Highly effective for fine particles; good chemical selectivity; adaptable through reagent formulation Reagent cost; sensitivity to water chemistry; requires optimization Moderate **environmental impact**, due to reagents and effluents Relatively moderate cost	(**Hanumantha Rao et al., 1990**). (**Mweene and Khanal, 2025**) (**Xu et al., 2023**) (**Liu et al., 2023**)
Leaching	Recovery: 75–90 (%) Purity: >98 (%)	Effective for mineral dissolution; potential to recover specific elements High chemical consumption; generation of waste streams; requires careful process control High **environmental impact**, due to reagent use and waste management challenges High cost	(**Baba et al., 2019**)
Hybrid flowsheets	Recovery: 85–95 Purity: 92–96	Combines strengths of multiple techniques; improved selectivity; enhanced recovery efficiency Increased process complexity; requires careful integration and optimization Reduced **environmental impact**, through optimized reagent use and lower waste generation Relatively moderate cost	(**Gougazeh, 2022**) (**Ahmed et al., 2023**) (**Aquilano et al., 2025**) (**Cinar and Durgut, 2019**)

Even more importantly, magnetic separation can contribute to the process optimisation by homogenizing the feed material for subsequent physico-chemical treatments, removing magnetic components that are otherwise challenging to process efficiently, decreasing the material load for downstream operations, and mitigating logistical constraints associated with material handling and transportation.

In a context influenced by the gradual depletion of ore deposits, the reduction in the particle size of ores and increasingly stringent environmental requirements, magnetic separation processes must evolve towards more selective, sustainable solutions adapted to the treatment of low-grade ores. Despite their environmentally-friendly nature, they still involve losses, hence the growing interest in advanced technologies such as centrifugal or high-gradient superconducting separators, which hold promise for the future of the mining sector (**Chen and Xiong, 2015**).

From a comprehensive perspective, gravity separation is low-cost, simple to implement and well suited to large throughputs, but it is sensitive to moisture, performs poorly on very fine particles and depends strongly on density contrast; it is typically effective for particles larger than 100µm and, depending on the equipment, can work down to roughly 20–50µm. Gravity separation, while cost-effective and environmentally benign, generally achieves moderate recovery and is best suited for coarse mineral fractions. Its efficiency relies on a significant density contrast between valuable minerals and gangue. However, in the case of silicate minerals such as feldspar and biotite, which are characterized by very similar densities, gravity separation increasingly difficult, its limitations become more evident when dealing with fine particles, where efficiency drops significantly, making alternative separation techniques necessary. The flotation method is highly effective for fine particles, it offers higher recovery rates (90–95%) and strong selectivity, particularly when reagents are carefully optimized (**Hanumantha Rao et al., 1990; Mweene and Khanal, 2025; R. Xu et al., 2023; Y. Liu et al., 2023**), yet it incurs reagent costs, is sensitive to water chemistry and requires careful optimization; it is generally applicable to particles below 200µm and particularly effective under 50µm. Flotation, by contrast, is often constrained by slower kinetics, higher operational costs, and significant environmental considerations related to chemical consumption and effluent treatment. It can be applied to mica minerals benificiation, including muscovite and biotite. However, achieving effective separation is challenging due to their similar surface properties and layered structures, which limit selectivity under conventional flotation conditions. As for magnetic separation, it is very selective for magnetic minerals, uses little water and can be compact, consistently provides high recovery and purity (85–90%) (**Khalifa et al., 2023; Xue et al.,**

2022; Ibrahim et al., 2002). In the case of silicate minerals such as feldspar and biotite, magnetic separation is the preferred method, as differences in magnetic susceptibility can be exploited to overcome the challenge posed by their similar densities, its applicable particle size range is variable and depends on the magnetic field strength, allowing treatment of both coarse and fine fractions when appropriately configured. Magnetic separation is cost-effective and efficient in terms of recovery, but it is ineffective for weakly magnetic minerals without activation and may require expensive high intensity magnets. Flotation offers high purity, at the cost of high reagent consumption. Leaching guarantees very pure products, but its cost and environmental impact are significant. Hybrid processes, by combining the strengths of several methods, enable the simultaneous optimisation of recovery, purity and sustainability (see **Table 3**). These findings suggest that no single method is universally superior, but rather, the choice depends on the mineralogical characteristics of the sample, the desired purity, and economic and environmental constraints. This synthesis underscores the importance of tailoring the separation strategy to the specific mineralogical context, and highlights opportunities for combined and hybrid approaches to overcome individual limitations.

5. Conclusions

Ceramic raw materials frequently contain trace magnetic particles embedded in biotite posing significant risks to the mechanical integrity of finished products. To commercially produce feldspar and quartz from granite waste, the main chemical challenge lies in minimizing iron oxide inclusions trapped within granite waste, particularly for feldspar, where such impurities significantly affect product quality. Due to its higher relative permeability and high content of iron ions capable of generating a magnetic moment, conferring paramagnetic behaviour, biotite reacts more intensely to the magnetic field, making it easier to capture by magnetic separation rather than by other methods, a property that can be exploited for its separation from feldspar and quartz, especially in the early stages of separation. The success of the separation depends on the dynamic equilibrium between the magnetic force exerted by the magnetic field and the competing opposing forces. Biotite responds differently to magnetic fields depending on particle size, crystalline state, chemical composition (particularly iron and manganese content), temperature, and the orientation of the field relative to its layered structure. it exhibits variable magnetic behaviour depending on the operating conditions, from typical paramagnetic attitude to an antiferromagnetic transition, where the magnetic moments align oppositely between the layers, while the pronounced crystalline magnetic anisotropy induced by its layered structure can also influence susceptibility depending on whether the field is applied in the plane of the layers or perpendicular to it. The effect of grain shape on separation is significant, particularly for fine particles, which are sensitive to magnetic field, gravity and centrifugal force. Physicochemical processes such as flotation and hydrometallurgy intend to be performed with fine particle sizes to ensure optimal separation efficiency, requesting significant grinding energy alongside their high reagent consumption. Hence, magnetic separation can participate on a large scale across different sectors, efficiently and cleanly. Advanced technologies in magnets manufacturing generate a high-gradient field at the surface, making them an effective solution for removing iron impurities from feldspar and quartz in granite waste. Dry magnetic separation provides excellent separation stability, given its extrusion structure and the high induction gradient it generates. Wet magnetic separation, on the other hand, performs satisfactorily, but is highly dependent on water flow rate and mixture viscosity. However, despite their petrographic similarity, granite waste materials exhibit specific characteristics and behave differently when treated, which has important implications for the applicability of separation methods. Variations in mineralogical assemblages, proportions of mica, feldspar, and quartz, as well as differences in grain size distribution, directly influence recovery efficiency and the choice of the most suitable technique. While the documented results are encouraging, extended studies remain necessary to fully assess their suitability for producing marketable products, particularly given the heterogeneity of granite waste. In addition, several barriers to industrial implementation of the reviewed separation techniques must be considered, including equipment scale and cost, process integration into existing flowsheets, material variability across sources, and the need for operational expertise. Industrial-scale implementation relies on the recovery of granite waste into useful minerals, reducing costs and creating value. Feasibility depends on raw material availability, regulatory compliance, supply chain stability, and adherence to environmental standards. Key challenges include reproducibility, product quality, process control, energy efficiency, waste management, and integration with existing production lines. Scaling up further requires maintaining efficiency at higher throughputs, ensuring uniform feed preparation, and managing increased energy and water demands. Pilot trials are essential to validate process stability before deployment. These constraints highlight the need for adaptable, cost-effective strategies and justify a dedicated discussion section supported by mineral processing literature.

Disclosure statement

No conflict of interest was reported by the author(s).

6. References

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SAŽETAK

Potencijal oporabe industrijskih minerala iz granitnoga otpada kao prilika za kružno gospodarstvo i ublažavanje utjecaja otpada: pregledna evaluacijska studija

Eksploatacija granita znatno doprinosi prekomjernom iskorištavanju prirodnih resursa uzrokujući negativne posljedice koje dovode do narušavanja ravnoteže ekosustava. Kao odgovor na rastuću potražnju javlja se hitna potreba za optimiranjem ne samo procesa u industriji granita nego i povezanih aktivnosti, poput gospodarenja otpadom, s ciljem povećanja održivosti i jačanja prijelaza prema kružnome gospodarstvu. Oporaba feldspata i biotita iz otpada granitne industrije predstavlja okolišno prihvatljivo i gospodarski opravdano rješenje koje obično uključuje niže operativne troškove te pridonosi smanjenju iscrpljivanja resursa i negativnih utjecaja otpada. S daljnjim tehnološkim razvojem biotit i feldspat imat će sve veću ulogu u različitim sektorima, uključujući energetiku, graditeljstvo i industrijsku primjenu. Aktualna istraživanja usmjerena su na poboljšanje učinkovitosti i održivosti metoda separacije radi dobivanja visokokvalitetnog feldspata s niskim sadržajem željeznih primjesa. Uz flotaciju, gravitacijsku separaciju i izluživanje, magnetska separacija ostaje učinkovita i okolišno prihvatljiva metoda izdvajanja željeznih oksida koji utječu na kvalitetu keramičkih proizvoda, pri čemu se postupak temelji na selektivnoj adsorpciji magnetskih čestica. Primjena suhoga ili mokroga postupka ovisi o različitim čimbenicima, kao što su kemijski i mineraloški sastav, granulometrijski sastav te okolišna ograničenja. Suhi postupak često ima prednost zbog praktičnih i ekoloških razloga, osobito pri proizvodnji visokokvalitetnih koncentrata za keramičku i druge industrijske primjene. Iako istodobna oporaba obaju minerala nije detaljno razmatrana, dostupna literatura navodi fizičko-kemijske kriterije koji utječu na njihovo ponašanje tijekom separacijskih postupaka.

Ključne riječi:
granitni otpad, feldspat, biotit, magnetska separacija, oporaba minerala

Author's contribution

Fatima Baila (PhD, mineral processing and environmental chemistry): conceptualization, investigation, methodology, writing - original draft and writing – review & editing. **Hamza Beniddar** (PhD, material sciences): investigation and review & editing. **Hasna Ait said** (PhD, analytical chemistry): data curation and visualization. **Yassine Darmane** (Full Professor in mineral processing and material sciences): project administration, supervision, validation, and writing – review & editing.
All authors have read and agreed to the published version of the manuscript.