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Physical Concentration of Heavy Minerals: A Brief Review on Low and High Intensity Magnetic Separation Process Techniques

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Choice selection and application variation of physical beneficiation techniques usually employed on heavy minerals (HMs) depends greatly on mineralogy, composition, shape, particle size distribution, and physicochemical properties of the minerals. Recent advancements in the applications of HM products by modern science, engineering, technological, and metallurgical production industries, especially in the demand by nuclear and power industries, have significantly increased over the decades. This is the reason for the criticality and commerciality of HM products, which has necessitated their high demand by various industries. The recovery of HMs, such as Zr, Hf, Ti, V, Sn, Pb, Cu, Zn, Fe, Mn, Nb, Ta, and REE associated minerals, from their deposits is dependent on the extractive metallurgy of transition and refractory metals from their complex minerals. However, based on the mineral concentration effectiveness, as well as the metal extraction efficiency, several challenges have been encountered in their recovery and separation from associated impurities. On this premise, this brief review is focused on investigating magnetic separation process applications in the beneficiation/recovery of HMs. This will serve as a tool for efficient mineral concentration and upgrade as well as reducing the process steps and extraction complexity involved in the downstream measures of dissolution/decomposition and pyro-hydrometallurgical separation processes.

INTRODUCTION

The essentiality and utility of heavy mineral (HM) resources in the world today cannot be overemphasized. There have been emerging interests in the HM concentration and upgrade as well as the industrial applications of HM sands. HMs such as columbite-tantalite (coltan) $(Fe,Mn,Mg(Nb,Ta)_2O_6)$, zircon $((Zr,Hf)SiO_4)$, ilmenite $(TiFeO_3)$, and rutile (TiO_2) are very important sources of niobium (Nb), tantalum (Ta), zirconium (Zr), hafnium (Hf), iron (Fe), titanium (Ti), and titanium dioxide, respectively. HMs do not have a standard scientific or industrial definition. They have been regarded as high-density accessory siliclastic sediment mineral constituents, as well as the minerals with specific gravity (SG) higher than that of the main constituent framework. They have also been regarded as the minerals with greater densities than that of quartz with about 2.65 g/cm^3. For instance, most HM sands (the siliclastic grains) are very dense with average SG above 2.9. Thus, minerals that possess a density property of ≥ 3.0 g/cm^3 are regarded as HMs.[1–5] As a result of their high density or SG, the minerals are often regarded as value HMs (VHM).[1] However, apart from the aforementioned VHM, other HMs still exist (see Table I) that may not necessarily be regarded as VHM (as that is dependent on the economical extractability and consumption). Chemical inertness and high strength are important attributes of

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Table I. Some HMs and their magnetic response or susceptibility to magnetism[1,2,6,22,40]

HMs	Chemical formula	SG	Magnetic response
Columbite-tantalite	Fe,Mn,Mg(Nb,Ta)$_2$O$_6$	5.2–8.2	Paramagnetic
Baddeleyite	ZrO_2	5.6–5.8	Diamagnetic
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$	2.7–3.1	Diamagnetic
Euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$	4.7–5.9	Paramagnetic
Kyanite	$Al_2O[SiO_4]$	3.5–3.7	Diamagnetic
Monzanite	$(Ce,La,Y,Nd,Th)PO_4$	4.6–5.7	Paramagnetic
Mullite	$Al_6Si_2O_{13}$	3.2	Diamagnetic
Staurolite	Fe_2^{2+} $Al_9Si_4O_{23}(OH)$	3.6–3.8	Paramagnetic
Andalusite	Al_2SiO_5	3.1–3.2	Diamagnetic
Leucoxene	$FeTiO_3$	3.6–4.3	Paramagnetic and diamagnetic
Sillimanite	$Al_2O(SiO_4)$	3.2–3.3	Diamagnetic
Tourmaline	$(Li,Al,Mn,Mg,Fe)_3(Cr,V,Fe,Al)_6$ $(BO_3)_3(Al,Si,B)_6O_{18}(F,OH)_4$	2.9–3.2	Paramagnetic and diamagnetic
Scheelite	$Ca(WO_4)$	6.1	Diamagnetic
Wolframite	$(Fe,Mn)WO_4$	6.7–7.5	Paramagnetic
Barite	$BaSO_4$	4.5	Diamagnetic
Xenotime	$(Y,Yb)(PO_4)$	4.4–5.1	Paramagnetic
Cassiterite	SnO_2	6.8–7.0	Diamagnetic
Ilmenite	$Fe^{2+}TiO_3$	3.9–4.1	Ferromagnetic and paramagnetic
Corundum	Al_2O_3	3.9–4.1	Diamagnetic
Monazite	$(Ce,Nd,La,Th,Y)PO_4$	4.6–5.7	Paramagnetic
Chalcopyrite	$CuFeS_2$	4.1–4.3	Diamagnetic and paramagnetic
Bornite	Cu,FeS4	4.9–5.0	Diamagnetic and paramagnetic
Hematite/magnetite	Fe_2O_3/ Fe_3O_4	5.2	Paramagnetic/ferromagnetic
Cuprite	Cu_2O	5.8–6.2	Diamagnetic
Chromite	$(Fe,Mg)(Cr,Al)_2O_4$	4.6	Paramagnetic
Garnet	Ca,Mg,Fe,Mn silicates	3.4–4.3	Paramagnetic and diamagnetic
Samarskite	$(Fe,Ca,U,Y,Ce)_2(Nb,Ta)_2O_6$	5.6–5.8	Paramagnetic and ferromagnetic
Spinel	$MgAl_2O_4$	3.6	Diamagnetic and paramagnetic
Pyrolusite	MnO_2	4.7–5.0	Diamagnetic and paramagnetic
Pyrite	FeS_2	5.0	Diamagnetic and paramagnetic
Pyroxene	$(Ca,Mg,Fe,Al)_2Si_2O_6$	3.1–3.6	Paramagnetic and diamagnetic
Pyrope	$Mg_3Al_2(SiO_4)_3$	3.5	Diamagnetic
Geothite	$FeO(OH)$	4.3	Paramagnetic
Pyrochlore	$(Na,Ca..)_2(Nb,Ta..)_2O_6[O,OH,F]$	4.2–4.4	Diamagnetic
Silica/quartz	SiO_2	2.7–3.0	Diamagnetic
Sphalerite	ZnS	3.9–4.0	Paramagnetic and diamagnetic
Zircon	$(Zr,REE,Hf)SiO_4$	4.6–4.7	Diamagnetic
Zincite	ZnO	5.7	Diamagnetic

Ti that are utilized by the medical and aerospace industries. In addition, over 95% of the supply of Ti is for the production of pigments. Furthermore, zircon is utilized mostly by the ceramics industries, by the foundry industries as foundry/refractory sand in the production of television screens, and a zirconia source in the chemical industries. The Murray Basin of West Australia, Tamil Nadu of India, and the sub-Saharan region of Africa are the world's largest sources of these HM sand resources.[6,7] The economic concentrations of Ti and Zr based or associated minerals can be found in certain primary magmatic mineral deposits as well as being naturally concentrated in sedimentary mineral deposits that could have gone through subsequent weathering.[1]

Pre-concentration of HM, often referred to as a mineral processing route, is focused on the rejection of waste (gangue) minerals in the early or initial stages of the mineral concentration process. This process step can be of significant benefit to mineral processing, in the sense that it provides lower mineral ore throughputs and costs of operation, as well as yielding increases in the grades of feeds to the downstream process routes.[8] The mineral ores that are amenable to pre-concentration at coarser particle size (PS) has cost-efficient mineral processing and subsequent beneficiation stages, as they require lower energy during the comminution process. The choice of the pre-concentration method to be adopted during processing and beneficiation of HMs depends on the minerals' physical and/or chemical properties or surface chemistry of the mineral ore, such as color, particle size distribution (PSD), SG difference, conductivity, magnetic susceptibility, and radioactivity between the gangue and value minerals.[8,9] The upgrade and beneficiation/extraction of most metals/transition metals from their minerals or ore deposits largely depends on the degree or measure of removal of the associated impurities present in the crude mineral.[10,11] For successful metal recoveries and (hydrometallurgical and pyro-hydrometallurgical) extractions, the impurity composition in the minerals/ore deposits, as well as the choice of beneficiation/extraction methods and/or extraction agents, are key.[11,12] Also, the success of the mineral beneficiation process steps is rated and dependent on the recovery percentage of high-purity value minerals with minimum impurity composition and a reduced number of processing or recovery steps.[11,13,14] Several reports from researchers have explained that most HMs, such as zircon, sillimanite, rutile, ilmenite, leucoxene, monazite, garnet, etc., are usually of low-grade, associated with large quantities or compositions of mineral impurities. For instance, zircon sand is mostly associated with Hf, Si, and/or Ti, P, Fe, Al, Y, U, and Th in HM forms, such as rutile, ilmenite, monazite, staurolite, pyrrhotite, quartz/silica, biotite, apatite, feldspars, titanite, plagioclase, amphibole, and limonite, as well as Te-Ti oxides and Cu minerals, etc. These impurities, especially Hf, have been proven very tedious and somewhat difficult to separate from Zr. This has made the mineral processing, beneficiation, and subsequent recovery/extraction of Zr very complex and complicated. Hence, efficient ore enrichment and certain mineral beneficiation process steps are essential and imperative. These are, however, carried out in order to effectively, efficiently, and significantly improve the metal recovery, as well as to enhance the performance of subsequent hydrometallurgical separation/extraction processes of the minerals or ore deposits for successful metal recovery.

Although, there is some difficulty in the beneficiation and separation of the value metallic elements and the associated gangue mineral impurities present in these mineral ores, and from one another due to their almost similar physicochemical mineral characteristics, there may be some slight differences, especially in certain properties, such as density or SG, boiling and melting point temperatures, conductivity and resistivity, radioactive properties, and, most essentially, their magnetic and electrical properties, whereby these minerals/metals can be exploited.[11,15–19] The preparation and upgrade of HMs and other low-grade minerals up to marketable technical grade concentrates may therefore involve basic physical beneficiation process routes, like the use of magnetic and electrostatic concentrations/separations prior to the (conventional and enhanced) gravity concentrations and froth flotation processes (involving physicochemical procedures), and/or pyro-hydrometallurgical process routes. Gravity concentration techniques have been regarded as the oldest and most common (pre)concentration process steps, usually employed on most HM sand deposits and aimed at the rejection of gangue minerals with low SG. However, the close densities of these HMs often pose major challenges during concentration by gravity.[8,15,20,21] Many physical mineral beneficiation processes (which include magnetic concentrations), that may preferably be carried out before/after flotation separations have been reported to practically upgrade low-grade minerals or ore deposits to high-grade concentrates and also improve the value metal separation and subsequent recovery from associated impurities in the mineral or ore deposit. Presently, magnetic concentration/separation has been regarded as a very important physical mineral processing and beneficiation technique. It has been reported to be a very promising concentration and separation technique employed in the exploitation and upgrade of various HMs, including Zr, Hf, Si, Ti, V, Sn, Pb, Cu, Zn, Nb, Ta, Fe, Mn, and REE-bearing minerals from their different ore deposits.[11,18,22–26] Several magnetic separation process techniques have been investigated and employed on various HMs and, hence, have been reported as being proven to be more efficient.[11,18,22–32] On this premise, therefore, this present paper is focused on a review of magnetic mineral processing/beneficiation process techniques of HMs, as well as on certain key areas for future development trends and process enhancements.

ESSENCE OF PHYSICAL ENRICHMENT PROCESS ON HMs

Mineral ores that contain HM can be obtained from low-grade primary or secondary sources or deposits. They usually undergo several subsequent physical separation techniques. However, the selectivity of these techniques is typically dependent on the physical and chemical properties of the minerals. This is often conducted in order to concentrate the mineral by beneficiating and separating the VHM from the unwanted mineral gangue or impurities. Mostly, certain mineral products or concentrates, such as columbite, tantalite, zircon, ilmenite, rutile, etc., are primarily obtained or result from these mineral processing or concentration techniques.[1] According to the studies by Nzeh et al.[11] and Koko,[33] physicochemical property differences existing between the value metal minerals and other gangue minerals or compounds can be utilized in the separation of the metals from each other and from the associated impurities, which aids and may improve the recovery and extraction of these HMs. Therefore, certain mineral impurities present in the metal minerals or ore deposits may be removed under certain mineral conditions, such as particle size and other specific separation parameters, prior to the hydrometallurgical extraction process. This may however be carried out in order to ease the difficulty and complexity of the mineral processing/metal extraction route, thereby feasibly reducing the metal extraction and recovery steps.[11,33] Furthermore, Gilman[34] suggested that these mineral processing and concentration techniques of HMs or mineral sands are somewhat benign, especially due to the employment of very few chemical reagents and also as a result of the presence of comparatively fewer legacy issues. In this regard, it is imperative for the ore enrichment/mineral beneficiation processes on the minerals/ore deposits to achieve proper concentrations and upgrading to an industrially acceptable grade (up to 25–50% for metals such as Ti, Zr, Hf, V, Sn, Pb, Cu, Zn, Fe, Mn, Nb, Ta, or REE). This will thereby aid the recovery effectiveness and efficiency of subsequent metal separation and extraction processes.[11,23–26,35,36] However, the mineral concentration techniques usually adopted can be either wet or dry. Detailed flow diagrams of the wet and dry magnetic concentrations of these HMs have been reported elsewhere.[1,11,36] Figure 1 displays a flow diagram of wet/dry concentrations of HMs.

MAGNETIC SEPARATION

Every material can be classified in terms of their magnetic characteristics. Thus, value HMs can be concentrated and beneficiated from the associated gangue/impurity minerals using magnetic concentrators, by exploiting their magnetic susceptibility differences which can be in one of three forms or categories, namely diamagnetic, paramagnetic, or ferromagnetic minerals. As such, mineral particles referred to as paramagnetic and ferromagnetic are attracted along the magnetic force field lines to higher magnetic field intensity points, whereas the mineral particles known as diamagnetic repel along the magnetic force field lines to lower magnetic field intensity points.[9,37–40] The ferromagnetic HMs are mostly and widely concentrated in magnetic concentrators, and have been reported to possess a certain high susceptibility level to magnetic force fields, and also to retain a certain degree or measure of magnetism even after the removal of the magnetic force field. However, the separation efficiency of ferromagnetic HMs is at high levels compared to the other forms of minerals (paramagnetic and diamagnetic).[38,40] On the other hand, diamagnetic minerals can also be separated from ferromagnetic minerals. Thus, magnetic force fields are used by magnetic concentrators in order to separate magnetic (ferromagnetic or highly paramagnetic) minerals from the nonmagnetic (weak paramagnetic or diamagnetic) minerals, which in either case may be gangue or value minerals. The magnetic portions may contain the value mineral while the nonmagnetic portion may have the gangue minerals or tailings. This may also occur vice-versa. In addition, paramagnetic minerals are not necessarily easy to separate and may require a higher intensity of the magnetic field for separation.[9,11,38,40] This magnetic application has, however, advanced over the decades, beyond just the removal of tramp iron. A review of the theory of magnetic separation of mineral particles and its mechanism is covered in detail elsewhere.[9,41–48] However, certain particle minerals are affected or influenced by magnetic concentration more than others. This simply means that the beneficiation of these minerals by means of magnetic separators may be more or less effective on some minerals. The performance or efficiency of the magnetic separators is, however, dependent on certain factors, which have been reported to be determinants in selecting or choosing the required magnetic concentration technique, as well as the optimal parameters or conditions. These factors include, but are not limited to, the magnetic intensity or magnetic field strength (measured in gauss or tesla), as well as the magnetic field gradient (shape) in the magnetic concentrating equipment, the mineralogical distribution, the PSD of the minerals, and the magnetism or magnetic characteristics possessed by such particle minerals.[9,11,30,49] Furthermore, the magnetic

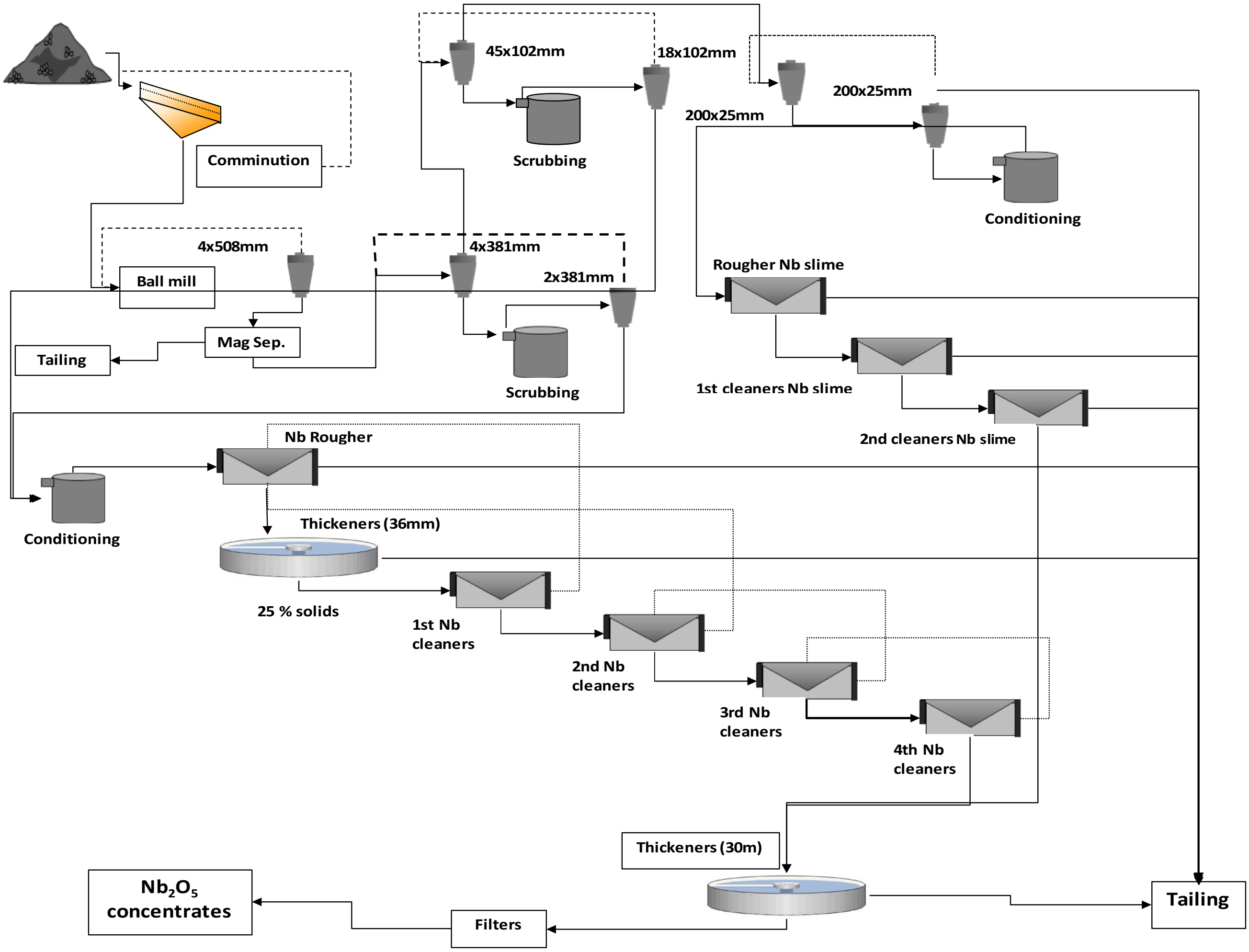

Fig. 1. Flow diagram of a typical HMs physical concentration treatment plant; reprinted with permission from Ref. 11.

characteristics in the mineralogy of different minerals have been investigated by various researchers. The differences in the magnetic characteristics or magnetism of these particle minerals are usually exploited when employing magnetic concentration as a technique in pre-, primary or secondary mineral concentration or upgrade, mineral processing, beneficiation, and extractive metallurgical processes.[11,50] Table I sets out certain HMs and their magnetic responses or susceptibilities to magnetism.

It has been established that high magnetic intensity magnetic separators tend to attract and separate ferromagnetic as well as strong or highly paramagnetic mineral particles as concentrates, while diamagnetic or nonmagnetic mineral particles are collected as tailings. Often, the weak paramagnetic mineral particles are also attracted to the high intensity magnets in the magnetic separators, depending on the degree or level of magnetic intensity of the magnets involved, as well as on the particle size of the minerals, as coarse mineral particles are somewhat more amenable or susceptible to magnets than finer mineral particles. However, magnetic separators with low magnetic intensity will attract and separate ferromagnetic mineral particles as concentrates while the paramagnetic and diamagnetic mineral particles are collected as tailings. Sometimes, the low intensity magnetic separators are also somewhat effective on the strong or highly paramagnetic minerals with coarse particle sizes, and will have these mineral particles included in the concentrates while the finer strong/highly paramagnetic, weak paramagnetic, and diamagnetic mineral particles are collected as the tailings.[11] Magnetic concentration can be either dry or wet. Albeit somewhat environmental challenges and eco-unfriendliness are often caused by the dry magnetic concentration method, it is, however, established as a simple and cost-effective technique and very efficient in mineral processing/beneficiation of HMs, as these minerals are usually composed of both diamagnetic and paramagnetic as well as ferromagnetic mineral particles.[11,40,51]

Wet magnetic concentration on the other hand is more complex and involves the use of a liquid (water) medium for separation. However, it is regarded to have smaller environmental issues or pollution because smaller amounts of dust particles are produced during the separation process, thus resulting in cleaner product.[9] Wet magnetic separators are also more effective in concentrating finer ferromagnetic particles (up to 75 μm) and/or (strong/weak) paramagnetic particles than dry magnetic separators.[30] In addition, more recent advancements in magnet technology and materials science have allowed the introduction and development of high intensity magnetic concentrators of up to 60,000 gauss (6 tesla). New demands for magnetic concentrators have thus been created as a result of the development of superconducting and permanent rare-earth magnets.[40] For instance, it has been reported that magnetic separation has been used in beneficiating and concentrating HM sands in order to remove highly ferromagnetic/ferrimagnetic particle minerals (such as magnetite) and highly paramagnetic minerals (such as xenotime, monazite, coltan, ferrocolumbite, and ferrotantalite) from several/various mineral ore deposits.[18,20,52,53] However, quartz/silica, zircon or other Zr-associated minerals are usually recovered from the nonmagnetic mineral portions. Pownceby et al.[30] reported that the mineral grains of certain HMs may be coated with clay or iron oxides, which as a result may affect the physical properties of the minerals, hence affecting or preventing subsequent/further physical beneficiation on the minerals. Various researchers have investigated the level or degree of efficiency of magnetic concentration on the mineral ore deposits of transition metals. However, magnetic concentration has been reported to be effective to a certain measure on complex oxide mineral ores, such as Ti, V, Ta, Nb, Zr, Hf, and other transition metals.[9,11,40,49]

The introduction of materials from rare-earth elements (REE) developed/advanced the usage of higher magnetic intensity or strength of permanent magnetic separators for beneficiation by the mineral sand industry.[30,54] There have been records of the adoption of several dry and wet magnetic separators for either high or low magnetic intensities, such as rare-earth drum magnetic concentrators (REDMC), roll magnetic concentrators (RERMC), and matrix-type magnetic separators. These magnetic separators were adopted in order to beneficiate HMs in various parts of the separating/processing system or circuit. For instance, dry low-intensity and wet high-intensity magnetic separators can be employed in order to beneficiate ilmenite from HM concentrates, such as Zr-containing minerals, when adopting magnetic concentration. Furthermore, dry high-intensity magnetic separators may then be utilized in order to eliminate the residual magnetic mineral particles obtained from the nonmagnetic portion that contains the zircon and rutile minerals.[30] Zircon sand, for example, has a very low magnetic susceptibility compared to other HMs. Thus, magnetic separation can be very efficient in the physical beneficiation/separation of most Zrassociated minerals for optimal mineral recoveries and high-grade Zr. However, there are limited applications of magnetic concentration on finer mineral particles of ≤ 75 μm. It is therefore imperative to note that magnetic concentration in general may not be satisfactorily efficient even when dealing with fine particles of mineral deposits below 100 μm. Thus, certain procedures such as froth flotation are usually required/employed (as a primary concentration or an adjunct process) on HMs with a PS of < 100 μm for improved beneficiation/separation efficiency.[18,30] Therefore, for higher separation efficiency, extraction effectiveness and process route simplicity, especially on finer mineral particles, magnetic concentration on these minerals is often employed combined with certain multiple adjunct processes, such as electrostatic concentration, gravity separation, and especially, froth flotation and aqueous (acidic or alkaline) leaching procedures.[11,18,20,51,55–60] For instance, Pownceby et al.[30] reported that certain individual HMs were beneficiated from their mineral concentrates in a dry processing plant employing a combination of magnetic and electrostatic concentrations, in order to separate and recover the associated magnetic mineral portions, such as ilmenite and that of the conducting mineral portions, such as rutile, respectively, from zircon mineral sand, which is a nonmagnetic/nonconducting mineral.[30,61] The authors also reported that gravity concentrations as well as the froth flotation process may also be adopted and employed as secondary concentration or adjunct beneficiation processes, in order to further beneficiate the initial concentrates.[30]

MAGNETIC CONCENTRATORS

Magnetic concentrators are reported as very useful in the separation of coarse mineral particles. There has been unusual enhancement of magnetic concentrators in the past few decades and, hence, the development of several classifications of magnetic concentrators, as well as various magnetic concentrator designs that beneficiate and concentrate HMs.[49,62] However, the most logical and practical classification is either wet or dry magnetic concentrators, which can operate at either high or low magnetic field intensities.[48,49] Svoboda and Fujita[49] reported that the magnetic field gradient is not taken into consideration in this scenario, and, thus, it is safe to say that high0intensity magnetic concentrators (a) will generate high magnetic field gradient (high gradient magnetic equipment), while low intensity magnetic concentrators (LIMC) are regarded as low gradient magnetic equipment, generating a low magnetic field gradient. Nevertheless, there may be exceptions to this rule. On this premise, the choice of magnetic concentrator classification may be factored by several considerations, most importantly the PS, the distribution of the feed mineral particles' magnetic characteristics, and the equipment's required throughput.[49] The wet MC procedure, however, was reported by Zong et al.[62] to require further processing, But, in contrast, the dry MC was reported to be more advantageous than the wet MC. For example, compared to a dry MC, a wet MC involves the consumption of water, the reuse of recycled water, and the management of mineral tailing ponds, etc. Apart from the wet and dry magnetic concentrators, other classifications of magnetic concentrators exist which may be grouped on the basis of magnetic field intensity/strength. This can also be split into electromagnetic concentrators which include (1) cross-belt magnetic concentrators (CBMC), (2) lift roller magnetic concentrators (LRMC), (3) induced roller magnetic concentrators (IRMC), and permanent magnetic concentrators, which include both RERMC) and REDMC. These are discussed in detail in.[9,38,40,62–64]

The trajectories of nonmagnetic mineral particles are obtained just by the force of centrifugation (centrifugal force). When nonmagnetic mineral particles such as zircon drop in an unhindered motion and substantially in the roller according to the mineral PS, the drop of mineral particles closer to the roller reduces their particle size fractions. However, larger mineral particles tend to move farther away from the roller's smaller centerline, often lower than the surface velocity of the smaller mineral particle concentrate. However, when a magnetic roller is utilized, the magnetic mineral particles which have higher magnetic fields often tend to stick on the magnetic roller surface until they are released from the magnetic force field. Furthermore, the magnetic mineral particles which have a weak magnetic field will only defect by the magnetic field, thereby causing them to deviate somewhat from the normal path; hence, the occurrence of overlapping in the coarser weak magnetic particles as well as in the finer nonmagnetic mineral particles.[38,62,65] Thus, Table II shows the working range of the different magnetic concentrators used by mineral processing and extractive metallurgical industries.

Dry and Wet Low-Intensity Magnetic Concentrators (LIMC)

LIMC are conventional magnetic concentrators mainly utilized in the removal of ferromagnetic (which includes basically iron) or certain highly paramagnetic HMs. This is mainly carried out in order to scalp the very magnetic mineral particles so as to enhance the performance of the permanent magnets/electromagnetic concentrators which are usually utilized in the separation of weak magnetic materials, or in order to protect the downstream operations like conveyor belts. These concentrators can utilize flux densities (of about 2000 gauss) and have the ability to treat dry solids and wet slurry.[9,40,58] The application of the dry LIMC is in the concentration of highly magnetic value minerals or the removal of highly magnetic mineral gangue/impurities and tramp iron. The dry LIMC is also mainly utilized in the concentration of coarse mineral sands composed of highly magnetic mineral particles. This procedure is often referred to as cobbing.[9,49] Magnetic drum concentrators are usually applied in the dry LIMC for the concentration of the highly magnetic value minerals, whereas plate and grate magnets, magnetic pulleys, and suspended magnets are utilized mainly for the removal of the mineral gangue impurities/tramp iron.[49] However, often, below 500 particle size, a dry LIMC is usually replaced by a wet LIMC.

Drum concentrators are also the most frequently employed wet LIMC, with concurrent-rotation and counter-rotation magnetic drum concentrators as the most common types. With the introduction of permanent ferrite magnets, the permanent magnetic system almost replaced the electromagnetic drum system. Thus, the concentrators are utilized basically in recovering and beneficiating HM media, which include zircon sand and ferrosilicon, as well as in a magnetic medium for the concentration of highly magnetic mineral ores, such as ferromagnetic sands and magnetite minerals. Moreover, the existence of rare-earth permanent magnets and their affordability increases the application of magnetic drum concentrators on moderate or weak magnetic mineral particles.[9,40,49] Practically, there are two designs involved in the permanent magnetic drum concentrators: the axial and radial configurations. The axial configuration or arrangement involves the poles alternating along the circumference. Its application is preferred when the magnetic product quality is actually of some significance, whereas the radial configuration/arrangement involves the polarity of permanent magnets alternating across the drum breadth, and its application essentially involves the recovery of highly magnetic mineral particles. Furthermore, the tumbling movements of mineral particles over rows of magnets coupled with alternate polarity tends to aid or assist the releasing of the nonmagnetic mineral particles entrained and, therefore, the concentrate grade is improved.[40,49]

Dry and Wet High Intensity Magnetic Concentrators (HIMC)

Reports have indicated that paramagnetic mineral particles are tedious, difficult, and somewhat impossible to beneficiate using a LIMC and thus require the HIMC process. These concentrators require higher magnetic flux densities up to 20,000 gauss ($\sim$ 2 tesla) in order to concentrate certain weakly magnetic (paramagnetic) mineral particles from the nonmagnetic ones.[40,58] There have also been reports that the HIMC are utilized in numerous applications by various mineral processing industries.[38] Hence, the emerging and

Table II. Working range of different magnetic concentrators used by mineral industries[38,66]

Concentrators	Type	Industrial working range (in tesla)
Dry permanent MC	DDMC	0–0.5
	REDMC	0.5–1.0
	Permanent roll/RERMC	1.5–2.0
Dry electro-MC	IRMC	2.0–3.0
	LRMC	2.0–3.0
	CBMC	1.5–2.0
	CDMC	1.5–2.0
Wet permanent MC	WDMC	0–0.5
	REWDMC	0.5–1.0
	FWMC	0.5–1.0
Wet electro-MC	WHIMC	1.5–2.0
	HGMC	1.5–2.0
	Open/close gradient MC	3.0–4.0
	RTWMC	1.5–2.0
	CSCC	4.5–5.0

DDMC dry drum magnetic concentrators, *REDMC* rare-earth drum magnetic concentrators, *RERMC* rare-earth roll magnetic concentrators, *IRMC* induced roll magnetic concentrators, *LRMC* lift roll magnetic concentrators, *CBMC* cross-belt magnetic concentrators, *CDMC* cross-disc magnetic concentrators, *WDMC* wet drum magnetic concentrators, *REWDMC* rare-earth wet drum magnetic concentrators, *FWMC* ferrous wheel magnetic concentrators, *WHIMC* wet high-intensity magnetic concentrators, *HGMC* high gradient magnetic concentrators, *RTWMC* roll-type wet magnetic concentrators, *CSCC* cryofilter super-conducting concentrators.

sustaining research on the performance evaluation of the (dry and wet) HIMC used in concentrating and beneficiating different HMs is inevitable. However, attempts have continuously been made by several technologists and researchers over the past decades to comprehend the beneficiation behavior of various HM particles in each of the (dry and wet) HIMC techniques, concentrating the different types of HMs with various levels of magnetic susceptibility. The inability of LIMCs to beneficiate paramagnetic minerals has consequently allowed the usage of HIMC applications over the years. In this regard, therefore, Tripathy et al.[38] concluded that dry HIMCs are still to find wide applications in the concentration and beneficiation of certain (paramagnetic) HMs, albeit the intense effort or investigations conducted by researchers. Dry HIMC application has thus undergone exceptional engineering and technological improvements over the past decades. Consequently, different approaches to novel designs and applications of the HIMC have emerged. Different efficient and effective magnetic concentrator types have evolved over the years with several varying designs and of a wide range of industrial importance. The literature has established that magnetic concentration may be employed as an integral step of a primary and/or secondary unit system in order to achieve the pre-concentration and/or concentration/beneficiation of mineral particles. Thus, dry HIMC applications have been accepted as the ideal magnetic concentration process in selectively concentrating/beneficiating and recovering paramagnetic mineral particles from various mineral sources or deposits.[38,67–69] Most dry HIMCs possess a higher magnetic field intensity which is imparted through induced magnetic fields or by a permanent magnet in order to separate the mineral particles with regard to their level of magnetic susceptibility.[38] Table III depicts the most common HIMCs and their major applications, as well as their most important characteristics and parameters or variables.

There are some other magnetic concentrators that fall under the category of dry HIMC which have also been investigated over the years by various researchers. These include the permanent roll, vibrating high gradient filter, open gradient, superconducting high gradient, and isodynamic magnetic concentrators.[38,39,49,67,68,70–81] Among these, the isodynamic tester/concentrator is usually employed primarily in order to obtain the quantitative analysis of paramagnetic minerals. It has also been widely employed in the characterization of minerals as well as the measurement of magnetic susceptibility, and also in stimulating grade and yield recovery curves. The high gradient high-intensity magnetic concentrators (HG-HIMC) and open gradient high-intensity magnetic concentrators (OG-HIMC) have not been successfully commercialized.[38] This was attributed to their inefficient magnetic field intensity/strength and as a result of the lack of uniform distribution of magnetic induction over the surface of the magnetic drums. However, HG-HIMC was mostly applied (at a laboratory scale) in the removal or separation of pyrite minerals from coal fines; it was found inefficient regardless.[38,44,76,77,82–86] However, research is still scanty in these areas (HG-HIMC and OG-HIMC) for efficient and cost-effective magnetic concentration. The dry type of HIMC is essentially utilized in the

Table III. Common HIMC, major parameters, characteristics and applications[38]

Concentrators	Maximum magnetic intensity/ strength	Parameters	Major characteristics/ properties	Major applications
Permanent roll/ RERMC	1.6 tesla	Feed rate, belt thickness, roll disk thickness, roll diameter, roll speed, splitter position, roll magnetic intensity, magnetic susceptibility, and particle size (PS).	Can be employed at various stages of concentration. Employed at a higher capacity and with better efficiency. Low belt life and requires frequent replacements.	Ilmenite, feldspar, (sub)bituminous coal, lignitic fly ash, bauxite, quartz/silica sand, lignite, perlite, colemanite, nepheline syenite, diamond, coal, semi coking coal, trona, wollstonite, Mn minerals, etc.
CBMC	2 tesla	Feed rate, applied current, main belt speed, pole air gap, coil current, cross belt speed and thickness, magnetic susceptibility, and PS.	The unit capacity is somewhat very low. It is utilized mostly as a cleaner process step.	Columbite, coltan, pyrochlore, tantalite, microlite, zircon, albite, cobalt, BOF and LD slags, Fe and Mn minerals, etc.
IRMC	2 tesla	Feed rate, rotor speed, rotor diameter, gap between rotor and pole, applied current, splitter position, magnetic susceptibility, and PS.	The magnetic intensity/ strength can be varied. Can be utilized as pre-concentrator, cleaner, or scavenger. Single unit process may be utilized in multi stage feed PS of 3 mm (coarser) and 75 μm (finer) mineral particles. Very low unit capacity.	Hematite, ilmenite, dolomite, garnet, magnesite, nepheline syenite, plant tailings, Cr, Mn, Sn, W minerals, etc.
LRMC	2 tesla	Feed rate, rotor speed, rotor diameter, gap between rotor and pole, applied current, splitter position, magnetic susceptibility, and PS.	Very low unit capacity. Utilized mostly as a cleaner. Magnetic intensity/strength can be varied. Feed PS of 3 mm (coarser) and 75 μm (finer) mineral particles.	Garnet, ilmenite, etc.

concentration of coarser mineral particles, even though the wet process is subsequently required as an adjunct process. Both dry and wet HIMCs have certain merits and demerits over each other. The dry HIMC is advantageous over wet HIMC in the sense that it avoids the consumption of water, the management of tailings ponds, the retrieval of water for re-use, and also less energy is consumed in the sense that pre-concentration is conducted on feed mineral particles at coarser size fractions or PS, followed by subsequent fine grinding for greater mineral liberation with smaller volume.

However, the dry HIMC has certain demerits or limitations which are not the case with the wet HIMC. These include inefficiency in the concentration and treatment of fine or ultrafine mineral particle size fractions, the control of dust particles in order to avoid polluting the atmosphere/air, and slime coating removal on coarser mineral products. Thus, the dry HIMC is more effective and efficient in the beneficiation of mineral particles with PS fractions greater than $-75+100$ μm. This is not the case with wet HIMC, as it is more efficient when beneficiating mineral particles with PS fractions below $-75+100$ μm of mostly paramagnetic mineral particles.[38] There have been reports that the manufacturers of dry magnetic concentrators were on top of the production of magnetic equipment that concentrates/beneficiates HM sand/placer beach sand mineral particles of size fraction of 45 μm. Also, in order to address the dust problems of dry magnetic concentrators, several process techniques have been employed by researchers in the past years. These process techniques include the mineral de-dusting process before subsequent concentration, as well as the addition of purge air between the feed and concentration/separation sections of the magnetic concentrators. More recently, there have been measures taken in order to curtail/address the demerits of HIMCa. Such measures have been in the design of the HIMC which include the design of its door, hopper, and frame systems. These were carried out so that the dust particles could be contained in the equipment during the concentration of the HMs. These units were, however, equipped internally with dust extraction design (per stage), were tunable, and also had purge air in cassettes in order to reduce the dust problems to a minimum. In the course of also addressing environmental problems caused by the dust pollution, a deeper, dust bag filter, as well as fluidized dust catchers, were implemented and integrated into the magnetic system. However, the cost economics of this procedure were not favorable.[38,87] In conclusion, therefore, Dobbins et al.[87] reported that the combinations of these process steps were regarded as enhancements for a better, safer, and cleaner environment, as well as improved part life and sustainability of the concentrator performance. Table IV summarizes the applications of different magnetic concentrators on certain minerals as investigated by various researchers.

SUMMARY

The efficacy of magnetic separation techniques on HMs has been studied. The choice selection/application variation of the physical beneficiation techniques usually employed on HMs depends greatly on the mineralogy, composition, shape, PSD, and the physical and/or chemical characteristics/properties of the minerals. Magnetic separation has been considered a necessary and suitable pre-/primary concentration technique with specific methodologies for mineral processing, ore beneficiation, and enrichment/upgrade. The process is usually conducted in order to concentrate HMs from associated elemental impurities/gangue minerals in the mineral and to ease the extraction complexity in preparation and optimization of the subsequent procedures, as well as to reduce the process steps involved in the downstream measures or hydrometallurgical separation processes. Furthermore, a comprehensive optimization process of the selected physical mineral processing or beneficiation technique is imperative, applying varying and differing variables/parameters in order to obtain the optimal beneficiation conditions involved in the physical processing of the minerals, as well as equipment type consideration. It is clearly deduced from the literature that magnetic separation has significant applications in the upgrade and beneficiation of HMs for the purpose of feasible downstream hydrometallurgical extraction of the value metals. The performance or efficiency of the magnetic concentrators is, however, dependent on certain factors or considerations, which have been reported to be determinants in the choice and selection of the required concentration technique as well as the optimal process parameters or conditions. These factors may include the strength of the magnetic field of the concentrator, the mineral's response or susceptibility level to magnetism, the distribution of the mineralogy, process/concentrator variables, characteristics/features, concentrator required throughput, strength, and applications, the PSD of the feed mineral particles, and the magnetic distribution characteristics possessed by such particle minerals.

There are, however, limited applications of magnetic separation on finer mineral particles of ≤ 75 μm size fractions. However, magnetic separation in general may not be satisfactorily efficient even when dealing with fine particles of mineral deposits up to 100 μm in particle size. Thus, a physicochemical procedure such as froth flotation is often employed (as a primary concentration or an adjunct process) on HMs with PS of < 100 μm for improved beneficiation/separation efficiency. However, the cost-intensiveness of the chemical reagents used and their environmental unfriendliness restrict the use of froth flotation. Hence, certain enhanced gravity concentration (EGC) procedures like centrifugal-assisted gravity concentration, or a combination of both physical and physicochemical concentration techniques, is recommended for effective recoveries of very fine mineral particles. Therefore, for higher or improved separation efficiency, extraction effectiveness and process route simplicity, especially on finer mineral particles, magnetic separation of these minerals is often employed combined with certain multiple adjunct processes, such as an EGC process, froth flotation, and, especially, aqueous (acidic or alkaline) leaching downstream procedures.

CONCLUSION

It can be concluded from this study that a wide HM variety may be concentrated/beneficiated in a dry HIMC. The main difference in HIMC techniques is simply based on capacity and separation efficiency. Among these are the IRMC and RERMC, which are often utilized as rougher and cleaner process at larger capacities. However, the CBMC and LRMC may be employed at cleaner stages as a result of the low handling capacity. The RERMC has been reported to be a cost-efficient unit system among other concentrators/techniques as a result of the high throughput and low energy consumption. In addition, between the IRMC and RERMC techniques, the IRMC possesses the demerit of being an electro-magnetic concentrator type, which significantly influences the operating cost of the concentration process. It also possesses flexibility in adjusting the magnetic field strength/intensity, which is simply on the basis of the change in the mineral feed properties/characteristics. Also, at the other end, the RERMC may be utilized in the upgrading process of coarse HM particle size fractions of between 75 μm and 10 mm. However, the concentration of the close range of particle sizes is more effective in these concentrator types, which tend to minimize the entrainment of finer mineral particles of lower magnetic susceptibility to the

Table IV. Summary of applications of different magnetic concentrators on minerals

Concentrator	Minerals	Parameters studied	Summary	References
IRMC	Brazilian zircon mineral concentrates	–	Elimination of magnetic ilmenites from zircon	Sampaio et al.[88]
	Indonesian high grade zircon-rich HM concentrates	–	Part of a flow diagram as a pre-concentration process of zircon and ilmenites	Aral et al.[89]
	Wolframite-scheelite-cassiterite mineral in Kyrgyzstan	–	Pre-concentrating Sn and W	Sreenivas et al.[90]
	Garnet fines	Feed rate, PS, magnetic intensity, splitter position, and rotor speed	Understanding effects of PS	Tripathy and Suresh[91]
	Indian hematites	Feed rate, PS, magnetic intensity, splitter position, and rotor speed	Separating hematite fines low-grade fines	Tripathy et al.[65]
	Egyptian magnesite-dolomite	Rotor speed and magnetic intensity	Separating Fe-associated magnesite from dolomite	Yehila and Al-Wakeel[92]
	Indian ferruginous chromites	Rotor speed and magnetic intensity	Separating ferruginous mineral impurities/gangues	Tripathy et al.[93]
	Turkish chromite tailings	Feed rate, rotor speed, and magnetic intensity	Cleaning and recovering value minerals	Aslan and Kaya[94]
	Indian Mn ores	Rotor speed, PS, and magnetic intensity	Enhancing Mn:Fe ratios by desliming and beneficiation	Tripathy et al.[95]
	Turkish nepheline syenite ores	Feed rate, PS, magnetic intensity, splitter position, and rotor speed	Rejecting Fe-associated mineral impuries/gangues	Ibrahim et al.[96]
	Indian ematites	Feed rate, rotor speed, and magnetic intensity	Separating hematite fines low-grade fines	Tripathy et al.[63]
	Sudan Fe ores	Rotor speed, PS, and magnetic intensity	Part of a flow diagram as a rougher and cleaning process	Seifelnassr et al.[97, 98]
	Indian chromite tailings	Rotor speed and magnetic intensity	Part of a flow diagram in order to enhance Cr:Fe ratio	Tripathy et al.[99]
	Indian ferruginous Mn ores	PS, magnetic intensity, splitter position, and rotor speed	Rejecting Fe-associated mineral impurities/gangues	Singh[100]
	Indian ferruginous chromites	Rotor speed and magnetic intensity	Cleaning and recovering value minerals	Tripathy et al.[101]
	Indian low-grade ferruginous Mn ores	Rotor speed and magnetic intensity	Part of a flow diagram as a 2-stage separation process	Singh et al.[102]
CBMS	South Korean fine dredged aggregate waste	–	Concentrating and recovery of the value heavy HMs (zircon, ilmenite, quartz, muscovite, monazite, magnetite, etc.)	Moscoso-Pinto and Hyung-Seok[103]
	Nigerian chromites	–	Enhancing Cr:Fe ratios	Abubakre et al.[104]
	Ti associated minerals in Sri Lanka	Magnetic intensity	Disk-type separation of Ti-associated minerals from beach sand minerals	Premaratne and Rowson[105]
	Nigerian columbites	–	Pre-concentrating process	Ayeni et al.[106]
	Slags from basic O_2 furnace steel making	Magnetic intensity	Separating Fe-associated phases	Wang et al.[70]

Table IV. Continued

Concentrator	Minerals	Parameters studied	Summary	References
	Nigerian columbites	PS, single and double stages	Part of a flow diagram as a 3 disk-type separation of columbites from impurities	Alabi et al.[58]
	Egyptian albite ores	Feed rate and magnetic intensity	Separating Fe and Ti compounds as impurities	El-Rehiem and El-Rahman[107]
	Indian low-grade siliceous Mn ores	Magnetic intensity and PS	Separating Mn-associated mineral particles	Mishra et al.[108]
	Indian cobalt-associated Mn ores	Magnetic intensity and PS	Separating Co-associated Mn mineral particles	Mishra et al.[109]
	Egyptian low-grade Fe ores	PS	Upgrading Fe composition of low-grade mineral ore	Al-Wakeel and El-Rahman[110]
	French Linz-Donawitz slags	Magnetic intensity	Separating Fe-associated phases	Menad et al.[111]
RERMC	Silica mineral sand	Splitter angle position, belt speed, and PS	Hematite removal	Ibrahim et al.[112]
	Turkish colemanites	Feed rate, splitter angle position, roll speed, and PS	Separating colemanites from impurities/gangues	Alp[113]
	Indian hematites	Feed rate, magnetic roll, splitter angle position, and roll speed	Separating hematite fines from low-grade fines	Tripathy et al.[114]
	Turkish semi-coked lignite	Feed rate, front and back splitter angle position, and roll speed	Reduction of ash and sulfur composition	Atesok et al.[115]
	Semi coked lignite of low-grade	Feed rate, splitter angle position, roll speed, and PS	Rejection of sulfur	Yildinm et al.[116]
	Ferruginous chromite mineral ores	Feed rate and roll speed	Separating ferruginous mineral impurities/gangue	Tripathy et al.[93]
	Indian bauxite mineral ore	PS and roll speed	Rutile, hematite, and goethite mineral separation	Bhagat et al.[117]
	Indian low-grade Mn siliceous mineral ores	PS	Upgrade of Mn composition	Dash et al.[118]
	Ferruginous chromite mineral fines	Feed rate and roll speed	Enhancing Cr:Fe ratios by Fe-bearing mineral removal	Tripathy et al.[66]
	Indian Teri sand, Ilmenite minerals	–	Ilmenite magnetic mineral concentration	Babu et al.[119]
	Turkish low-grade coals	–	De-sulfurization and de-ashing procedure	Celik[120]
	Turkish Mn mineral ores	PS	Separation of Mn-associated minerals	Atesok et al.[121]
	Low-grade Fe siliceous ore fines	PS	Upgrade of Fe composition	Dwari et al.[122, 123]
	Indian charged chrome slags	Roll speed	Separation of chrome metal from slags	Shen and Forssberg[124]
	Turkish lignite fly ash	Roll speed and PS	Pre-concentration and separation of Fe-associated compounds/impurities	Ozdemir and Celik[125]
	(Sub)bituminous coal	–	Separation of shale	Oder[126]
	Indian charged chrome slags	Roll speed	Separation of chrome metal from slags	Das et al.[127]

Table IV. Continued

Concentrator	Minerals	Parameters studied	Summary	References
	UK coals	–	Pyrite separation from coal	Saeid et al.[128]
	Trona in USA	Splitter angle position and PS	Trona pre-concentration and elimination of illite and dolomitic shale	Ozdemir et al.[129]
	Lignite in USA	–	Separation of macerals	Order et al.[130]
	Turkish lignite	Feed rate, splitter angle position, roll speed and PS	Rejection of sulfur	Koca et al.[131]
	Egyptian nepheline syenites	Feed rate, PS and rotor/belt speed	Removal of Fe-associated mineral impurities/gangues	Ibrahim et al.[96]
	Greek bauxite mineral ore	–	Separation of calcite from bauxite	Stamboliadis and Kailis[132]
	Turkish Mn mineral ore	PS	Separation of braunite	Grieco et al.[133]
	Turkish feldspar	Magnet:steel ratio and PS	Removal of Fe-associated mineral impurities/gangues	Gülsoy and Orhan[134]
	Israel perlite	–	Removal of Fe-associated mineral impurities/gangues	Herskovitch and Lin[135]
	Turkish feldspar	PS	Separation of colored magnetic particles	Gülsoy et al.[136]

magnetic stream. Thus, a magnetic concentration system circuit comprised of a combination of these concentrators may assist in the separation efficiency, as well as economics, of the concentration process of specific complex paramagnetic HMs.

RECOMMENDATIONS

It is evident that, from the descriptions made in the published literature, a high demand exists in the adoption of a simple, cost-effective, and eco-friendly physical beneficiation route for concentrating certain HMs, such as the magnetic, paramagnetic, diamagnetic, conducting, and nonconducting HM particles. Although much research has been conducted in this area, the complexity of certain mineral processing routes as a result of the complex mineralogy of the HM deposits, and also the accompanied environmental unfriendliness, is still a major constraint in the beneficiation and recovery of HMs. Thus, proper mineral characterization, as has been reported and/or discussed elsewhere,[11,24–26,137–139] and hence the exploitation of the mineral's physicochemical properties/characteristics, as well as the exploration, exploitation, and optimization of the various process techniques involved in the physicochemical beneficiation of HMs, are highly imperative. The evaluation of the feasibility study of physical separation techniques/concentrators on HMs often meets a major challenge. This is not far from developing a suitable mineral characterization strategy in order to comprehend the magnetic properties/characteristics distributed among the particles of the HM deposits. Currently, there is an intense need for the development/enhancement of efficient mineral processing routes on, especially, paramagnetic concentrators for the recovery of fine paramagnetic low-grade HM deposits. The literature does not completely incorporate the process route, parameters, and operating principles, as well as the various applications, and thus information in the study area is somewhat scanty, hence further research investigation is imperative.

In furtherance of this, future research should be focused on the inter-twined effects analyses of PS, density/SG, and their magnetic susceptibility/responses, as well as their behavior in a magnetic force field with certain operating and designing parameters/variables of the processes and concentrators. In addition, therefore, applications in the concentration of various (para-) magnetic minerals with very complex mineralogy need to be fully explored. Also, the challenge existing in the use of HIMCs for magnetic concentration may be resolved if the science behind the movement of mineral particles or the particle motion physics involved in magnetic separation is completely understood, as well as the distribution of the magnetic susceptibility/responses of the feed mineral deposits. In conclusion, for a successful, feasible, efficient, less complex, cost-effective, and eco-friendly hydrometallurgical downstream extraction of HM concentrates, the development of proper mineral processing/physicochemical beneficiation process routes is essential. Thus, in achieving optimal yield results in the mineral upgrade and concentration, high separation efficiencies, grade purities, and mineral recovery, the effective/efficient optimization and control of the process parameters/variables or system conditions involved in the adopted HM physicochemical beneficiation process route, are therefore imperative and thus recommended. Hence, this can be achieved through the aid of a Taguchi–Anova design and model by the proper experimental design process of the involved concentration procedures and, thus, should include suitable experimental process optimizations as well as comprehensive engineering modeling, and/or simulation mechanisms of various aspects of such beneficiations.

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CONFLICT OF INTEREST

On behalf of all the authors, the corresponding author hereby declares that there are no known (financial) competing interests or conflicts of interests related to this article which could influence or affect the study.

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REFERENCES

1. C. Perks and G. Mudd, *Ore Geol. Rev.* 107, 629 (2019).
2. H. Elsner, *Heavy Minerals of Economic importance* (Federal Institute for Geosciences and Natural Resources, Germany, 2010).
3. IAEA. Safety Reports Series, No. 51, Vienna, Austria, 1–115 (2007).
4. M.A. Mange and H.F. Maurer, *Heavy Minerals in Colour* (Springer, Netherlands, 1992).
5. A.C. Morton, *Heavy Minerals in Provenance Studies. Provenance of Arenites* (Springer, Dordrecht, 1985).
6. I.W. Morley, *Black Sands: A History of the Mineral Sand Mining Industry in Eastern Australia/I.W. Morley* (University of Queensland Press, St. Lucia, 1981).
7. R.M. Tyler and R.C.A. Minnitt, *J. S. Afr. Inst. Min. Metall.* 104, 89 (2004).
8. C. Marion, T. Grammatikopoulos, S. Rudinsky, R. Langlois, H. Williams, P. Chu, M. Awais, R. Gauvin, N. Rowson, and K.E. Waters, *Miner. Eng.* 121, 1 (2018).
9. B.A. Wills and T.J. Napier-Munn, *Will's Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*, 7th edn. (Elsevier Science and Technology Books, Amsterdam, 2006).
10. O.M. El-Husaini and M.N. El-Hazek, *Eur. J. Miner. Process. Environ. Prot.* 5(1), 7 (2005).
11. N.S. Nzeh, S. Adeosun, A.P. Popoola, A. Adeleke, and D. Okanigbe, *Miner. Process. Extr. Metall. Rev.* 43(7), 833 (2022).
12. Y. Zhang, M. Du, B. Liu, Z. Su, G. Li, and T. Jiang, *Sep. Sci. Technol.* 52(7), 1321 (2017).
13. M. Nete, *Dissolution and Analytical Characterization of Tantalite Ore, Niobium Metal and Other Niobium Compounds (Published Dissertation)*, University of the Free State, Bloemfontein, pp. 1–22 (2009).
14. M. Nete, *Separation and Purification of Niobium and Tantalum from Synthetic and Natural Compounds (Published Thesis)*, University of the Free State, Bloemfontein, pp. 1–36 (2013).
15. A. Jordens, Y.P. Cheng, and K.E. Waters, *Miner. Eng.* 41, 97 (2013).
16. A. Jordens, C. Marion, O. Kuzmina, and K.E. Waters, Investigating the use of froth flotation to beneficiate a rare earth mineral deposit, in *Presented at the XXVII International Mineral Processing Conference*, Santiago, Chile, pp. 1–11 (2014).
17. A. Jordens, R.S. Sheridan, N.A. Rowson, and K.E. Waters, *Miner. Eng.* 62, 9 (2014).
18. A. Jordens, C. Marion, R. Langlois, T. Grammatikopoulos, N.A. Rowson, and K.E. Waters, *Miner. Eng.* 99, 111 (2016).
19. A. Jordens, C. Marion, R. Langlois, T. Grammatikopoulos, R.S. Sheridan, C. Teng, H. Demers, R. Gauvin, N.A. Rowson, and K.E. Waters, *Miner. Eng.* 99, 96 (2016).
20. J. Zhang and C. Edwards, Review of rare earth mineral processing technology, in *Presented at the 44th Annual Meeting of the Canadian Mineral Processors (CIM)*, Ottawa, Canada. CIM J, vol. 4, no. 1, pp. 38–52 (2013).
21. C.K. Gupta and N. Krishnamurthy, *Extractive Metallurgy of Rare Earths* (CRC Press, Boca Raton, 2005).
22. G.B. Abaka-Wood, K. Quast, M. Zanin, J. Addai-Mensah, and W. Skinner, *Powder Technol.* 344, 897 (2019).
23. R.H. Nielsen, J.H. Schlewitz, H. Neilsen, and H. Kirk-Othmer, *Encyclopedia of Chemical Technology* (Wiley Online Library, Hoboken, 2007).
24. N.S. Nzeh, A.P.I. Popoola, A.A. Adeleke, and S.O. Adeosun, *Mater. Today Proc.* 65, 2184 (2022).

25. N.S. Nzeh, M. Mokgalaka, N. Maila, P. Popoola, D. Okanigbe, A. Adeleke, and S. Adeosun, *Pyrometallurgy—New Perspectives*, Intechopen, pp. 1–23 (2023).
26. N.S. Nzeh, P. Popoola, S. Adeosun, and A. Adeleke, Characterization of Rayfield-Jos columbite deposit for efficient beneficiation and recovery of niobium and tantalum, in *Presented at the Minerals, Metals and Materials Society 2023 Conference. The Minerals, Metals & Materials Series*, pp. 191–206 (2023). https://doi.org/10.1007/978-3-031-22576-5_18.
27. E. Lobato, *Brazilian Mining Technical Report 49—Profile of Zirconita*, Ministry of Mines and Energy (MME) (2009).
28. J. Ward, *World Supply and Demand for Zirconium Minerals: Current Position and Future Prospects*, Commonwealth of Australia, Geoscience Australia, pp. 1–52 (1970).
29. H. Klemic, Zirconium and hafnium minerals, in *Industrial Minerals and Rocks*, 4th edn. ed. by S.J. Lefond (Society of Mining Engineers, Englewood, 1975).
30. M.I. Pownceby, G.J. Sparrow, H. Aral, L.K. Smith, and W.J. Bruckard, *Miner. Process. Extr. Metall.* 124(4), 240 (2015).
31. E. Snyders, J.H. Potgieter, and J.T. Nel, *J. S. Afr. Inst. Min. Metall.* 105, 459 (2005).
32. K.M. Punis, *Quality* 33, 36 (1994).
33. F. Koko, *Niobium and Tantalum Beneficiation from Tantalite Ore (Published Thesis)*, University of the Free State, Bloemfontein, pp. 1–26 (2013).
34. S. Gilman, *Min. Eng.* 60 (2008).
35. A.R. Adetunji, W.O. Siyanbola, I.I. Funtua, S.O.O. Olusunle, A.A. Afonja, and O.O. Adewoye, *J. Miner. Mater. Charact. Eng.* 4(2), 85 (2005).
36. G. Jones, An overview of the industry, in *Presented at the Seventh International Mining Geology Conference*, The AusIMM, Perth, WA, Iluka Resources Ltd Publication (2009).
37. A. Tripathy, S. Bagchi, S.K. Biswal, and B.C. Meikap, *Chem. Eng. Res. Des.* 117, 520 (2017).
38. S.K. Tripathy, P.K. Banerjee, N. Suresh, R. Murthy, and V. Singh, *Miner. Process. Extr. Metall. Rev.* 38(6), 339 (2017).
39. R.K. Dwari and K.H. Rao, *Miner. Process. Extr. Metall. Rev.* 28, 177 (2007).
40. P. Venkatraman, F.S. Knoll, and J.E. Lawver, *Soc. Min. Metall. Explor. Inc* 7, 221 (2003).
41. D.V.S. Rao, *Mineral Beneficiation: A Concise Basic Course* (CRC Press, Boca Raton, 2011), pp109–114.
42. P. V. Iyer, *SME Mining Engineers Hand Book*, ed P. Darling (Society of Mining, Metallurgy and Exploration, Colorado, USA 2011), pp. 1533–1545.
43. Y.S. Karmazin, V.I. Shute, V. Yu, and L.Z. Grebenyuk, *Magn. Electr. Sep.* 10, 35 (1999).
44. V.V. Karmazin, *Magn. Electr. Sep.* 8, 139 (1997).
45. M. Broek, *Magn. Electr. Sep.* 6, 213 (1995).
46. D.G. Morgan and W.J. Bronkala, *Magn. Electr. Sep.* 3, 5 (1991).
47. D.G. Morgan and W.J. Bronkala, *Magn. Electr. Sep.* 4, 151 (1993).
48. J. Svoboda, *Magnetic Methods for the Treatment of Minerals* (Elsevier, Amsterdam, 1987).
49. J. Svoboda and T. Fujita, *Miner. Eng.* 16, 785 (2003).
50. A. Shikika, M. Sethurajan, F. Muvundja, and M.C. Mugumaoderha, *Hydrometallurgy* 198, 1 (2020).
51. G.G. Berhe, D.R.A. Velazquez, Y. Abubeker, W. Girma, and T. Bogale, *Int. J. Miner. Metall. Mater.* 24(7), 727 (2017).
52. T. Tran, New developments in the processing of rare earths, in *Presented at the International Conference on Rare Earth Minerals and Minerals for Electronic Uses*, Prince Songkla University, Hat Yai, THA, pp. 337–353 (1991).
53. C.J. Ferron, S.M. Bulatovic, and R.S Salter, Beneficiation of rare earth oxide minerals, in *Presented at the International Conference on Rare Earth Minerals and Minerals for Electronic Uses*, Prince Songkla University, Hat Yai, THL, pp. 251–269 (1991).
54. B.R. Arvidson, *The Austalasian Institute of Mining and Metallurgy*, pp. 131–136 (2001).
55. R. Chi, S. Xu, G. Zhu, J. Xu, and X. Qiu, Beneficiation of rare earth ore in China, in *Technical Sessions at the 130th TMS Annual Meeting*, TMS Aluminum Committee, New Orleans, USA, pp. 1159–1165 (2001).
56. M. Nete, W. Purcell, E. Snyders, J.T. Nel, and G. Beukes, *J. S. Afr. Inst. Min. Metall.* 112, 1079 (2012).
57. M. Nete, F. Koko, T. Theron, W. Purcell, and J.T. Nel, *Int. J. Miner. Metall. Mater.* 21(12), 1153 (2014).
58. O.O. Alabi, S.A. Yaro, G.T. Dungka, F. Asuke, and B. Hassan, *J. Miner. Mater. Charact. Eng.* 4, 181 (2016).
59. W. Purcell, H. Potgieter, M. Nete, and H. Mnculwane, *Miner. Eng.* 119, 57 (2018).
60. M.S. Cheru, A.V. Del Rosario, A.Y. Ali, G.G. Berhe, and B. Tadesse, *JOM* 70(12), 2807 (2018).
61. H.H. Dunkin, *Australas. Inst. Min. Metall.* III, 230 (1953).
62. Q.X. Zong, L.Z. Fu, and L. Bo, *E3S Web Conf.* 53, 1 (2018).
63. S.K. Tripathy, P.K. Banerjee, and N. Suresh, *Powder Technol.* 264, 527 (2014).
64. B.R. Arvidson and D. Norrgran, *Society for Mining, Metallurgy & Exploration*, pp. 223 (2014).
65. S.K. Tripathy, V. Singh, Y.R. Murthy, P.K. Banerjee, and N. Suresh, *Int. J. Miner. Process.* 160, 16 (2017).
66. S.K. Tripathy, P.K. Banerjee, and N. Suresh, *Int. J. Miner. Metall. Mater.* 22(3), 217 (2015).
67. D.A. Norrgran and M.J. Mankosa, *Society for Mining, Metallurgy and Exploration, Inc.*, Colorado, USA, pp. 1069–1093 (2006).
68. A. Russell, *Industrial Minerals*, pp. 39–57 (1992).
69. L.A. Roe, *Mining Engineering*, pp. 1261–1965 (1958).
70. D. Wang, M. Jiang, C. Liu, Y. Min, Y. Cui, J. Liu, and J. Zhang, *Steel Res. Int.* 83(2), 189 (2012).
71. L. Chen, G. Liao, Z. Qian, and J. Chen, *Int. J. Miner. Process.* 102–103, 136 (2012).
72. J.H.P. Watson and P.A. Beharrell, *Miner. Eng.* 19, 1580 (2006).
73. J. Svoboda, *Magnetic Techniques for the Treatment of Materials: Reviews of Magnetic Separators* (Kluwer Academic Publishers, London, 2004).
74. W.J. Bronkala, *Magnetic Separation (Ullman's Encyclopedia of Industrial Chemistry* (Wiley-VCH Verlag GmbH and Co. KGaA, New Jersey, 2000).
75. A. Ciesla, *Magn. Electr. Sep.* 3, 219 (1992).
76. S.S. Banerjee and S.G. Dixit, *Fuel Sci. Technol. Int.* 10(10), 1653 (1992).
77. A.C. Lua and R.F. Boucher, *Coal Prep.* 8(1–2), 61 (1990).
78. J.A. Wernham, M.J. Ross, J.N. Orlich, and D. Norrgran, *Design and Installation of Concentration and Dewatering Circuits*. ed. by A.L. Muler and M.A Anderson, pp. 478–497 (1986).
79. J.H.P. Watson and D. Rassi, Single-wire magnetic separation: A diagnostic tool for mineral processing, in *Presented at the 50th International Conference on Mineral Science and Technology*, Mintek, Sandton, South Africa, Randburg, South Africa: The Council for Mineral Technology, 26–30 March, 1984.
80. J.H.P. Watson, Magnetic separation at high magnetic field, in *Presented at the 6th International Cryogenic Engineering Conference*, IPC Science and Technology Press Ltd, Grenoble, France (1976).
81. J.H.P. Watson, *Superconducting magnetic separation*. ed. by B. Seeber (Bristol, UK: Institute of Physics Publishing, 1998), pp. 1371–1406.
82. Y.A. Liu, K.R. Hamby, and D.R. Colberg, *Powder Technol.* 64, 3 (1991).
83. C. Van Driel, J. Sikkenga, and C. Kerkdijk, *J. Phys. Colloq.* 45(C1), C1-775 (1984).
84. N.C. Lockhart, *Powder Technol.* 40, 17 (1984).
85. Y.A. Liu, *Physical Cleaning of Coal*. ed. by Y.A. Liu (New York: Marcel Dekker, 1982), pp. 133–254.
86. E.C. Hise, A.S. Holman, and F.J. Friedlaender, *IEEE Trans. Magn.* 17(6), 3314–3316 (1981).
87. M. Dobbins, P. Dunn, and I. Sherell, *The Southern African Institute of Mining and Metallurgy*, pp. 63–70 (2009).

88. C.H. Sampaio, S. Sabedot, and H. Wotruba. *Characterization and Beneficiation of a Northeastern Brazilian Zircon*. https://www.researchgate.net/publication. Accessed 13 October 2023.
89. H. Aral, M.I. Pownceby, and J. Im, *Appl. Earth Sci. (Trans. Inst. Min. Metall. B)* 117(2), 77 (2008).
90. T. Sreenivas, K. Srinivas, R. Natarajan, and N.P.H. Padmanabhan, *Miner. Process. Extr. Metall. Rev.* 25, 193 (2004).
91. S.K. Tripathy and N. Suresh, *Adv. Powder Technol.* 28, 1092 (2017).
92. A. Yehia and M. Al-Wakeel, *Physicochem. Probl. Miner. Process.* 49(2), 525 (2013).
93. S.K. Tripathy, Y.R. Murthy, V. Singh, and N. Suresh, *Miner. Process. Extr. Metall. Rev.* 37(3), 196 (2016).
94. N. Aslan and H. Kaya, *Arab. J. Sci. Eng.* 34(2B), 285 (2009).
95. S.K. Tripathy, P.K. Banerjee, and N. Suresh, *Int. J. Miner. Metall. Mater.* 22(7), 661 (2015).
96. S.S. Ibrahim, H.A. Mohamed, and T.R. Boulos, *Physicochem. Probl. Miner. Process.* 36, 173 (2002).
97. A.A.S. Seifelnassr, E.M. Moslim, and A.Z.M. Abouzeid, *Physicochem. Probl. Miner. Process.* 48(2), 567 (2012).
98. A.A.S. Seifelnassr, E.M. Moslim, and A.Z.M. Abouzeid, *Int. J. Miner. Process.* 122, 59 (2013).
99. S.K. Tripathy, Y.R. Murthy, and V. Singh, *Int. J. Miner. Process.* 122, 47 (2013).
100. V. Singh, *Miner. Metall. Process* 26(3), 127 (2009).
101. S.K. Tripathy, V. Singh, and Y. Ramamurthy, *Int. J. Min. Eng. Miner. Process.* 1(3), 101 (2012).
102. V. Singh, T.K. Ghosh, Y. Ramamurthy, and V. Tathavadkar, *Int. J. Miner. Process.* 99(1), 84 (2011).
103. F. Moscoso-pinto and K. Hyung-seok, *Minerals* 11(49), 1 (2021).
104. O.K. Abubakre, R.A. Muriana, and P.N. Nwokike, *J. Miner. Mater. Charact. Eng.* 6(2), 143 (2007).
105. W.A.P.J. Premaratne and N.A. Rowson, *Eur. J. Miner. Process. Environ. Prot.* 4(3), 183 (2004).
106. F.A. Ayeni, I.A. Madugu, P. Sukop, S.A. Ibitoye, A.A. Adeleke, and M. Abdulwahab, *J. Miner. Mater. Charact. Eng.* 11(6), 587 (2012).
107. F.H. El-Rehiem and A. El-Rahman, *Miner. Process. Extr. Metall.* 117(3), 171 (2008).
108. P.P. Mishra, B.K. Mohapatra, and K. Mhanta, *J. Miner. Mater. Charact. Eng.* 8(1), 47 (2009).
109. P.P. Mishra, B.K. Mohapatra, and P.P. Singh, *J. Miner. Mater. Charact. Eng.* 8(4), 317 (2009).
110. M.I. Al-Wakeel and M.K. El-Rahman, *Miner. Process. Extr. Metall.* 115(4), 177 (2006).
111. N. Menad, N. Kanari, and M. Save, *Int. J. Miner. Process.* 126, 1 (2014).
112. S.S. Ibrahim, M.M. Farahat, and T.R. Boulos, *Part. Sci. Technol.* 35(1), 21 (2017).
113. I. Alp, *J. S. Afr. Inst. Min. Metall.* 108, 139 (2009).
114. S.K. Tripathy, V. Singh, Y.R. Murthy, P.K. Banerjee, and N. Suresh, *Int. J. Miner. Process.* 160, 1631 (2017).
115. G. Atesok, K.T. Perek, H. Dincer, and M.S. Celik, *Coal Prep.* 20(3–4), 79 (1999).
116. I. Yildinm, H. Yiice, G. Onal, and M.S. Celik, Upgrading of low-rank semi-coked lignite by high intensity dry magnetic separator, in *Paper Presented at the Changing Scopes in Mineral Processing*, Balkema, Rotterdam (1996).
117. R.P. Bhag, B. Banerjee, A.T.P. Saha, and B.C Mukherjee, Dry magnetic separation of bauxite ore, in *Paper Presented at the International Seminar on Mineral Processing Technology*, Chennai, India (2006).
118. N. Dash, B.K. Mohapatra, and D.S. Rao, *World Metall. ERZMETALL* 63(2), 5 (2010).
119. N. Babu, N. VasumathI, and R.B. Rao, *J. Miner. Mater. Charact. Eng.* 8(2), 149 (2009).
120. M.S. Celik, *Coal Prep.* 22, 311 (2002).
121. G. Atesok, M. Ozer, H.D. Atesok, and F. Burat, Beneficiation of Ankara–Haymana region manganese ores by magnetic separation method, in *Paper Presented at the XIII International Mineral Processing Symposium* (IMPS 2012), Bodrum, 10–12 (2012).
122. R.K. Dwari, D.S. Rao, and P.S.R. Reddy, *Int. J. Min. Sci. Technol.* 23, 1 (2013).
123. R.K. Dwari, D.S. Rao, and P.S.R. Reddy, *J. Inst. Eng.* 95(2), 115 (2014).
124. H. Shen and E. Forssberg, *Waste Manag.* 23, 933 (2003).
125. O. Ozdemir and M.S. Celik, *Can. Metall. Q.* 41(2), 143 (2002).
126. R.R. Oder, Dry magnetic separation of ash, sulfur and mercury from Southwestern Wyoming coal, in *Paper Presented at the 18th International Low Rank Fuels Symposium*, Billings, Montana, 24–26 June 2003.
127. B. Das, J.K. Mohanty, P.S.R. Reddy, and M.I. Ansari, *Scand. J. Metall.* 26(4), 153 (1997).
128. A.M. Saeid, D.A. Butcher, and N.A. Rowson, *Magn. Electr. Sep.* 4(2), 107 (1993).
129. O. Ozdemir, V. Gupta, J.D. Miller, M.E. Cinar, and M.S. Celik, *Miner. Metall. Process* 28(2), 55 (2011).
130. R.R. Order, R.S. Weinstein, and R. J. Snoby, Combined air jig and dry magnetic separator for cleaning coal, in *Paper presented at the Twentieth Annul International Pittsburgh Coal Conference*, Pittsburgh, PA (2003).
131. H. Koca, S. Koca, and O.M. Kockar, *Miner. Eng.* 13(6), 657 (2000).
132. E.T. Stamboliadis and G. Kailis, *Eur. J. Miner. Process. Environ. Prot.* 4(2), 84 (2004).
133. G. Grieco, S. Kastrati, and M. Pedrotti, *Miner. Process. Extr. Metall. Rev.* 35(4), 257 (2014).
134. O.Y. Gülsoy and E.C. Orhan, *Physicochem. Probl. Miner. Process.* 38, 301 (2004).
135. D. Herskovitch and I.J. Lin, *Magn. Electr. Sep.* 7, 145 (1996).
136. O.Y. Gülsoy, N.M. Can, and I. Bayraktar, *Miner. Process. Extr. Metall. (Trans IMM: Sec. C)* 114(2), 80 (2005).
137. N.S. Nzeh, A.P.I. Popoola, D. Okanigbe, S.O. Adeosun, and A.A. Adeleke, *Mater. Today Proc.* https://doi.org/10.1016/j.matpr.2023.08.059 (2023).
138. N.S. Nzeh, A.A. Adeleke, and A.P. Popoola, *Physicochem. Probl. Miner. Process.* 59(3), 1 (2023).
139. N.S. Nzeh, A.P. Popoola, D. Okanigbe, S. Adeosun, and A. Adeleke, *Heliyon* 9, 1 (2023).