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Abstract

The mineral wealth of Colombia is a significant contributor to economic growth; however, it also generates a considerable amount of waste, which presents an opportunity for the implementation of circular economy initiatives. This study assesses the viability of utilizing mining waste from El Bagre, Antioquia, to produce magnetic nanoparticles for energy applications. A sample of black sand concentrate from alluvial gold mining, provided by Mineros Aluvial S.A., was subjected to X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) analyses to ascertain its elemental and mineralogical composition before and after a magnetic separation process, demonstrating a significant increase in the concentration of magnetite from 14 to 73%. Furthermore, an enhancement in the saturation magnetization of the material was observed, suggesting its potential utility in the formulation of ferrofluids, which are employed in a diverse array of applications.

Key words: agnetic nanoparticles; Mining wastes; Magnetite; Ferrofluids; Circular economy; black sands.

Identificación de Fuentes de Residuos Mineros para la Producción de Nanopartículas con Aplicaciones Energéticas

Resumen

La riqueza mineral de Colombia contribuye significativamente al crecimiento económico; sin embargo, también genera una cantidad considerable de residuos, lo que presenta una oportunidad para la implementación de iniciativas de economía circular. Este estudio evalúa la viabilidad de utilizar residuos mineros de El Bagre, Antioquia, para producir nanopartículas magnéticas para aplicaciones energéticas. Una muestra de concentrado de arena negra proveniente de la minería aluvial de oro, suministrada por Mineros Aluvial S.A., fue sometida a análisis de fluorescencia de rayos X (FRX), difracción de rayos X (DRX) y microscopía electrónica de barrido con espectroscopia de dispersión de energía (SEM-EDS) para determinar su composición elemental y mineralógica antes y después de un proceso de separación magnética, demostrando un aumento significativo en la concentración de magnetita del 14 al 73%. Además, se observó una mejora en la magnetización de saturación del material, lo que sugiere su potencial utilidad en la formulación de ferrofluidos, que se emplean en una amplia gama de aplicaciones.

Palabras clave: Nanopartículas magnéticas; Residuos mineros; Magnetita; Ferrofluidos; Economía circular; Arenas negras.

1. Introduction

Colombia's complex geological history has resulted in the formation of a diverse range of mineral resources. The extraction of these resources has constituted a significant factor in the country's economic growth, representing 2.4% of gross domestic product (GDP) in 2023 (Asociación Colombiana de Minería (ACM), 2024). The mining sector is responsible for the creation of approximately 209,000 direct jobs and nearly 750,000 indirect jobs (ACM, 2024), thus contributing decisively contributor to employment opportunities in Colombia. While the mining sector offers a range of economic benefits, it is widely acknowledged that mining activities result in the generation of significant quantities of waste (Jawadand & Randive, 2021). Nevertheless, there is a possibility that these wastes could serve as an intriguing raw material, or even a value-added raw material, for other industries, including the energy industry.

Gold, copper and ferronickel concentrates are considered strategic minerals and pillars of Colombian mining exports, with average production of 52; 1,248 and 38,736 tons per year, respectively, between 2020 and 2022 (Agencia Nacional de Minería, 2023b; Unidad de Planeación Minero Energética (UPME), 2024). However, beyond its direct economic value to produce electronic devices and batteries, the residues generated in its processing are presented as a valuable source of materials for other sectors (El Abboubi & San, 2023).

The growing energy demand, driven by globalization and industrialization, has underscored the urgent need for sustainable energy sources. The depletion of fossil resources has accelerated the search for cleaner and more efficient alternatives (Panwar et al., 2011; Shahsavari & Akbari, 2018). In this regard, recent technological advances have opened new possibilities for improving energy efficiency, particularly in the thermal sector, which is fundamental to the majority of industrial processes (Departamento Nacional de Planeación, 2017; Naciones Unidas, 2022).

The effective transfer of thermal energy is a crucial aspect in various industrial processes, where the utilization of suitable working fluids plays an indispensable role. Historically, pure substances such as water and oils have been employed for this purpose (Younes et al., 2022). Nevertheless, the pursuit of enhanced yields has prompted the integration of nanoparticles into these fluids. The incorporation of these particles into the base fluid results in a notable enhancement of the thermal properties, thereby optimizing heat transfer and facilitating the development of more efficient and versatile systems (Evangelisti et al., 2019). In contrast, ferrofluids, a distinctive category of nanofluids endowed with magnetic characteristics, provide an enhanced degree of precision and adaptability. The application of an external magnetic field allows for the precise modulation of the thermal conductivity of the fluid, rendering them a powerful tool for optimizing the performance of a range of thermal systems, including solar collectors, fluid cooling and heating system (Hedayatnasab et al., 2017; Younes et al., 2022).

The synthesis of magnetic nanoparticles requires the selection of an appropriate method, which may include coprecipitation, thermal decomposition, laser ablation, chemical reduction, or biogenesis. The choice of method is contingent upon factors such as size control, shape, purity, and scalability (Jamkhande et al., 2019).

In this context, the present study examines the potential of utilizing waste from mineral beneficiation to obtain base materials for the formulation of ferrofluids, with possible thermal applications, which effectively contribute to the energy transition and circular economy by employing waste in the production of high-value materials.

2. Methodology

2.1 Material selection methodology

A review of the scientific and technical literature was conducted with the objective of identifying the key chemical elements for obtaining nanoparticles applied in ferrofluids for thermal use. This information was then used as a starting point for the selection of mining-metallurgical wastes. The geological environments in Colombia that contain these elements were described in order to determine their presence as minerals associated with the production of gold, nickel, and copper. These minerals represent a significant portion of the non-energy resources extracted in the country and have been identified as strategic for the national energy transition (Agencia Nacional de Minería, 2023a), in addition to their notable contribution to formal mining.

To ascertain the provenance of the selected ore, a combination of geological and statistical data was employed to identify the regions of the country with the highest historical production of gold, copper, and nickel. To restrict mining output to specific conditions of availability and accessibility of mining-metallurgical residues, regional data were cross-referenced with mining operators in possession of deposits of the selected mineral. The historical production data were obtained from the Unidad de Planeación Minero-Energética (UPME), while the geological information was extracted from documentary sources available in the literature.

Revista EIA | https://doi.org/10.24050/reia.v22i44.1851

Subsequently, mining companies operating in the defined regions of the country were identified, along with their exploitation licenses and information regarding the composition of their deposits. This information was used to ascertain whether the mining wastes produced by these companies might contain minerals of interest for obtaining iron, cobalt, or nickel nanoparticles. In addition, the presence of minerals presents in the deposits that can be considered associations to the mainly extracted minerals and their different recovery methods were evaluated.

2.2 Characterization of selected sample

A compositional characterization was conducted on a representative sample obtained from the selected deposit using the quartering method. This was done in order to determine the proportion of the different minerals present and to validate the previous geological data. Subsequently, the sample was subjected to a concentration process using a Carpco MIH(13)111-5 induced-roll type high-intensity magnetic separator, operating in a laboratory setting at a speed of 327 rpm and an electric current of 0.12 A. From this process, a concentrated fraction of the material was obtained, which was characterized to verify the increase of magnetic minerals compared to the original sample.

Both samples were subjected to X-ray fluorescence (XRF) analysis using a Malvern Epsilon 1 instrument and X-ray diffraction (XRD) analysis with a Malvern-PANalytical Model Empyean 2012 diffractometer equipped with a Cu source (λ=1.541874 Å), operated at 45 kV and 40 mA, with a step size of 0.02° and a time per step of 52 seconds. Furthermore, a scanning electron microscope (SEM) coupled to an energy dispersive spectroscopy system (EDS, model JSM-6490) was employed to examine the surface microstructure of the material and perform qualitative and semi-quantitative identification of the elements present. Scanning electron microscope (SEM) coupled with energy-dispersive spectroscopy (EDS) measurements were conducted under 20 kV conditions. Finally, room temperature magnetization curves were constructed for the original sample and the concentrated sample using a vibrating sample magnetometer (Quantum Design), with the objective of comparing the saturation magnetization (Ms), coercive field (Hc), and remanent magnetization (Mr) parameters.

3. Analysis and discussion of results

The magnetic properties of ferrofluids employed in thermal applications must meet specific criteria to enable effective interaction with magnetic fields, thereby optimizing heat transfer in industrial processes. The most desirable properties are high saturation magnetization, low coercivity, and thermal stability. In this context, compounds of iron, cobalt, and nickel are particularly well-suited for this specific application due to their magnetic properties. These three elements form the basis of the magnetic nanoparticles most commonly used in obtaining ferrofluids due to their intrinsic characteristics (Evangelisti et al., 2019; Hedayatnasab et al., 2017; Younes et al., 2022).

In Colombia, the principal manifestations of iron, as a primary mineral extraction, are situated in the departments of Boyacá and Casanare, where they occur in the form of iron layers. Additionally, banded iron formations are present in the municipality of Mitú, replacement deposits in Cundinamarca and Boyacá, and iron prospects resulting from magmatic segregation in the Sierra Nevada de Santa Marta, the Cordillera Central, and the Serranía del Perijá (Prieto R. G. et al., 2019). Iron occurs in a variety of mineral forms, either as a native mineral or in compounds. Among these, oxides are of particular note, including magnetite, wüstite, maghemite, and hematite, as well as hydroxides, with goethite being one of the most common. In Colombia, these minerals are found in deposits such as Buriticá (Antioquia), Marmato (Caldas), Vetas (Santander) and Cajamarca (Tolima), which were formed from magmatic processes. They also appear in placer-type deposits, such as those of lower Cauca (Antioquia), Playa de Oro (Chocó) and the Rionegro region (Santander), and as a result of the decomposition of primary iron sources (Acosta - Luna et al., 2022; Alvarán et al., 2011; Bartos et al., 2017; Chavéz, 2023; Gleeson et al., 2004; Kerguelen, 2016; Leal-Mejía et al., 2017; Lesage et al., 2013; López, 2018; Naranjo et al., 2018; Nieto, 2019; Prieto R. G. et al., 2019; D. Ramírez, 2020; G. Ramírez & Portilla, 2006, 2003; Santacruz Reyes, 2016; Valls et al., 2019).

Revista EIA | https://doi.org/10.24050/reia.v22i44.1851

In contrast, the historically exploited nickel concentrations in Colombia are primarily located in the Cerro Matoso mine. This mine is composed of a sedimentary succession that rests on an ultramafic body that is integrated into the continent. This ultramafic body is part of the Cauca Ophiolithic Complex. This rock assemblage was attached in northwestern Colombia during the Upper Cretaceous period through the Romeral Fault System and subsequently exposed to weathering processes during the last Andean orogeny (Castrillón et al., 2023; Mejia & Durango, 1983; Tobón, 2018).

With regard to cobalt, there are currently no official reports on the production of cobalt as a principal ore in Colombia. Nevertheless, cobalt has been identified as a minor mineral constituent in several mineral deposits. Notable among these are orthomagmatic deposits, massive sulfides in Chocó, nickeliferous laterites in Córdoba, as well as some mines of hydrothermal origin in the mining district of Vetas and California in Santander (López, 2018; Prieto R. G. et al., 2019; D. Ramírez, 2020).

In light of the paucity of data on cobalt, the fact that ferronickel is the material produced at the Cerro Matoso mine, and the availability of data on iron ores in mining projects in Colombia, iron compounds are selected for a more detailed analysis among these three options. This decision is made in accordance with the objective of this study, which is to examine the potential for generating added value from mining waste. Table 1 presents a list of iron minerals that may be considered in the selection process of nanoparticle sources, along with their most salient properties in the context of the proposed application.

Table 1. *Iron minerals and their properties*

Mineral	Chemical formula	Thermal properties	Type of magnetism	Reference
Hematite	Fe_2O_3	Stable up to 1,560 °C, high melting point; good conductor of heat.	Antiferromagnetic at low temperature but may be weakly ferromagnetic.	(Bigham et al., 2002)
Magnetite	Fe_3O_4	Good thermal conductor, stable up to about 1,580 °C.	Ferrimagnetic; high saturation magnetization.	(Evangelisti et al., 2019)
Maghemite	γ-Fe_2O_3	Thermal stability similar to magnetite, but with lower magnetization. Ferrimagnetic.	Ferrimagnetic.	(Shokrollahi, 2017)
Wüstite	FeO	Stable at elevated temperatures, but oxidizes rapidly; melting point around 1,370 °C.	Paramagnetic at room temperature.	(Bigham et al., 2002)
Goethite	α-FeOOH	Thermally decomposes around 250-300 °C, forming hematite.	Antiferromagnetic.	(Bigham et al., 2002)
Metallic iron	Fe	High melting point (~1,538 °C), excellent thermal conductor.	Ferromagnetic at room temperature.	(Kittel, 2005)

As evidenced in Table 1, minerals such as hematite, wüstite, and goethite are devoid of the requisite magnetic properties for incorporation into ferrofluid formulations. Conversely, although metallic iron exhibits exemplary magnetic characteristics, its inherent chemical instability could result in premature oxidation during heating and cooling cycles. Ultimately, magnetite and maghemite are identified as the most promising candidates for ferrofluid formulation, exhibiting a favorable balance of magnetic properties and enhanced chemical stability. Nevertheless, no information was discovered regarding the potential applications or benefits of maghemite in Colombian mining waste.

Revista EIA | https://doi.org/10.24050/reia.v22i44.1851

While magnetite is associated with a wide variety of deposit types, including porphyry-type deposits related to intrusives, iron oxide-copper-gold deposits (IOCG), skarn-type deposits, and massive sulfide mineralizations (VMS) (Sillitoe et al., 2020), in Colombia it is primarily linked to gold mineralizations. This is due to the fact that, from a geochemical perspective, gold exhibits a positive correlation with iron and sulfur in magmatic settings, accompanying these elements throughout the evolution of magmatic series(Vivallo et al., 1995). This geochemical affinity between iron and gold is also reflected at the metallogenic level, where both elements can be found associated in the same deposit or in separate but closely related deposits within the same metallogenic province (Vivallo et al., 1995).

Table 2 provides a summary of the materials of interest in Colombia that can be used to obtain nanoparticles

Table 2. Summary of the materials of interest in Colombia.

Localization	Mine	Region	Exploited mineral	Mineral content	Quantity of mineral	Residue extraction method	Reference
Antioquia	Mineros S.A /Nechí Alluvial	Lower Cauca - Nechí river alluvial valley	Gold	109 mg/m3 in proved reserves	279,702 ton/year	Magnetic separation	(Kerguelen, 2016)
	Zijin-Continental Gold Limited/ Buriticá	Buriticá (Antioquia)	Gold	20.4 g/ton in measured resources	Not defined	Not defined	(Acosta - Luna et al., 2022; Bartos et al., 2017; Leal-Mejía et al., 2017; Lesage et al., 2013)
	Tamana pacific/Lucky mine	Lower Cauca -Nechí	Gold	No data	Not defined	Magnetic separation	(Chavéz, 2023)
Caldas	Aris Mining Corporation/ Marmato	Marmato	Gold	4.31 g/ton in proved reserves	Not defined	Not defined	(Bartos et al., 2017; Leal-Mejía et al., 2017; Santacruz Reyes, 2016)
Chocó	Atico Mining Corporation/ El Roble	Carmen de Atrato	Copper and gold	3.85 % Cu in proved reserves	Not defined	Magnetic separation and flotation	(D. Ramírez, 2020)
	La Esperanza mine	Playa de oro	Gold	No data	Not defined	Not defined	(Nieto, 2019)

Table 2. Summary of the materials of interest in Colombia.

Localization	Mine	Region	Exploited mineral	Mineral content	Quantity of mineral	Residue extraction method	Reference
Córdoba	South32 Limited/ Cerro Matoso	Montelíbano	Ferronickel	1.2 % in reserves	Not defined	Reduction	(Gleeson et al., 2004; López, 2018; Prieto R. G. et al., 2019)
Santander	Alicanto Colombia S.A.S/ Rionegro	Rionegro y Lebrija	Gold	0.81 g/t in inferred resources	4,787,644 m^3	Not defined	(Valls et al., 2019)
	Los Delirios mine	Vetas	Gold and silver	5.53 g/ton in indicated resources	Not defined	Not defined	(G. Ramírez & Portilla, 2003)
	La Tosca mine	Vetas	Gold and silver	5.53 g/ton in indicated resources	Not defined	Not defined	(G. Ramírez & Portilla, 2006)
Tolima	AngloGold Ashanti/La Colosa	Cajamarca	Gold	Not defined	Not defined	Not defined	(Bartos et al., 2017; Leal-Mejía et al., 2017; Naranjo et al., 2018)
	Río Frío mine	Payandé	Copper	Not defined	Not defined	Not defined	(Alvarán et al., 2011)

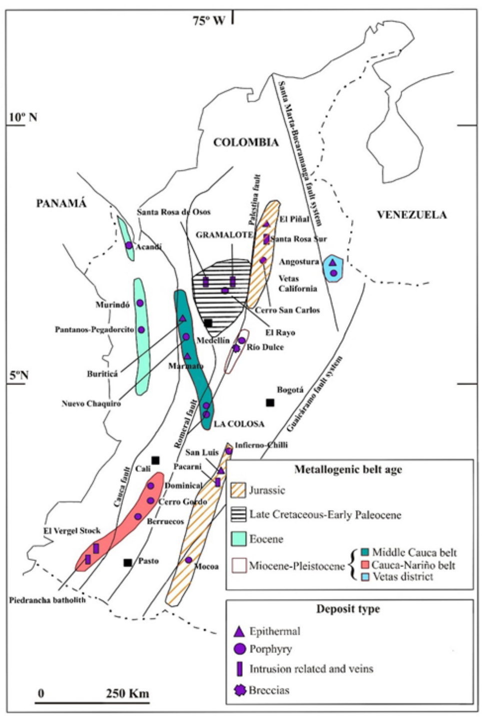
As shown in Table 2, there is an intimate relationship between magnetite and gold and prevalence of gold mining projects in Colombia that contain magnetite. For this reason, an exhaustive review of the gold deposits in the country was carried out. Given that gold is one of the most important minerals extracted in Colombia, with a production of up to 55 tons in the last ten years (Agencia Nacional de Minería, 2023b), this analysis is particularly pertinent in order to gain a deeper understanding of the opportunities and challenges associated with the extraction and exploitation of magnetite.

Gold in Colombia is found in a variety of deposit types, which have developed over a long evolutionary history. The gold deposits in Colombia can be divided into five geological periods: the Precambrian (Proterozoic), Triassic-Jurassic, Cretaceous, Paleogene, and Neogene (Prieto R. G. et al., 2019). Table 3 presents a summary of the types of gold-bearing deposits found in Colombia, along with their respective locations.

Table 3. Types of gold deposits in Colombia. Taken from Prieto et al. (2019).

Deposit Type	Location
Gold placers	Lower Cauca, Nechí, Porce, and Anorí rivers (Segovia-San Lucas zone); La Miel and Samaná rivers (Antioquia); Saldaña river (Ibagué-Mocoa); Patía, Iscuandé, Tapaje, and Naya rivers (Anchicayá-Piedrancha zone); San Juan river (Chocó); Cuiari (Guainía); Taraira (Vaupés); Naquén and Caranocoa mountains (Guainía).
Gold and platinum placers	Acandí, Bagadó, Tadó, Condoto, Istmina, Nóvita, Sipí, Lloró, Quibdó (Chocó); Atrato and San Juan rivers and their tributaries.
Vein deposits	Segovia and Remedios (Antioquia); San Lucas mountains (Bolívar); Vetas-California (Santander); Santa Isabel-Líbano-northern Ibagué (Tolima); Santa Cruz (Nariño, Anchicayá-Piedrancha zone). Notable mines: El Silencio (Segovia), El Limón (Zaragoza), La Bramadora (Guadalupe), Vetas (California), Marmato (Marmato), La Equis (Quibdó), El Diamante (La Cruz).
Skarn-type deposits	Mina Vieja and El Sapo mine (Payandé, Tolima); Ibagué-Mocoa zone (Central Cordillera).
Massive sulfide deposits	El Roble Project (El Carmen, Chocó).
Copper porphyries	Murindó (Antioquia); Acandí (Chocó); Pisno páramo (Silvia, Cauca); La Colosa (Cajamarca, Tolima).
Thermal springs	El Piñal (San Lucas mountains, Bolívar).

Figure 1. *Mineralized and magmatic belts of Colombia, showing known gold-bearing deposits. Modified from Naranjo et al. (2018).*



Historical gold production in Colombia has been concentrated primarily in the departments of Antioquia and Chocó, with lesser production occurring in other departments, including Bolívar, Cauca, and Nariño. In recent years, production has been concentrated in the departments of Antioquia, Chocó, Bolívar, Córdoba, and Caldas (UPME, 2024). The largest gold production is associated with deposits of alluvial origin and emplacement, as well as processes related to magmatic bodies (Shaw et al., 2019).

Figure 2. *Gold production by department in Colombia 2012-2023. Source: Modified from UPME (2024).*

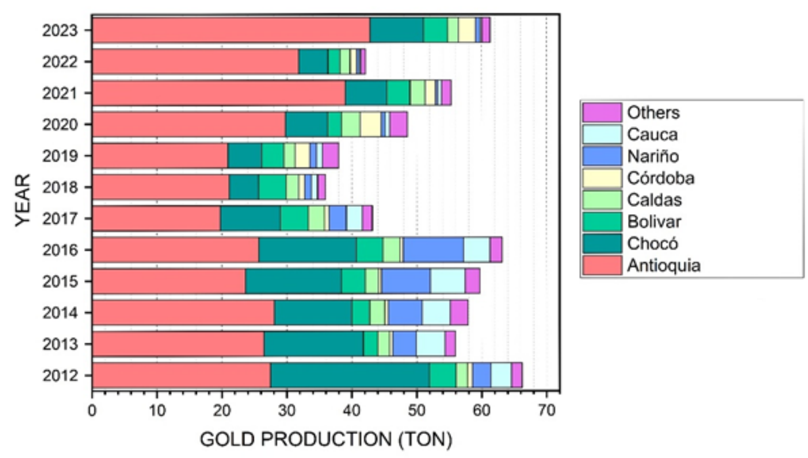
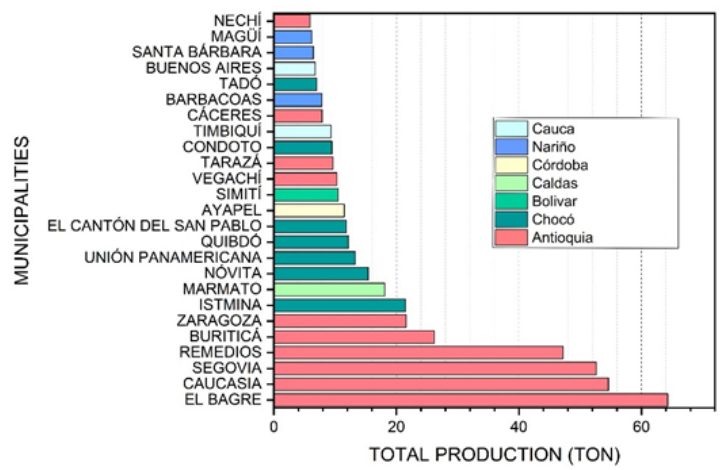


Figure 3. *Gold production by municipality in Colombia 2012-2023. Source: Modified from UPME (2024).*



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Based on historical production data provided by UPME (2024) and Shaw et al., (2019) the availability of data on the presence of minerals of interest in mining waste, and the recovery methods of the mineral of interest for each case, it is proposed that the mining waste of El Bagre, in lower Cauca region of Antioquia, represents the greatest opportunity for its exploitation.

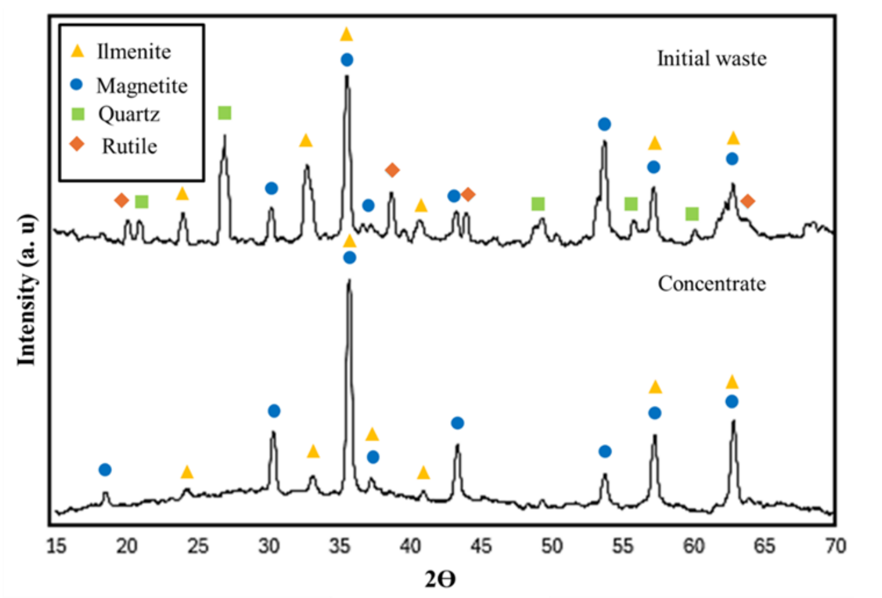
By modeling drilling data from Mineros S.A. of 1949, Kerguelen, (2016) estimated the presence of approximately 263.4 kg of gold and 417 tons of black sands in an area of 171,326 m^2, contained in a volume of 1,838,013 m^3 of alluvial material. Furthermore, Kerguelen estimates that the black sands contain 8.2% by weight of magnetite. Given this proportion and the average production of Mineros - Nechí Alluvial of 21,545.6 kg of gold between 2018 and 2022 (Mineros S.A, n.d.), it can be calculated that the average annual amount of magnetite to be disposed of is 279,702 tons.

In regard to the characterization of the selected mineral source, a sample of 100 kg of black sand concentrate from El Bagre was initially obtained. This sample was then subjected to four stages of quartering, resulting in the production of a representative sample of 6.25 kg for its elemental and compositional characterization. The results of the XRF analysis for the elemental composition of the initial sample and the concentrate obtained by magnetic separation are presented in Table 4. The XRD results are shown in Figure 4.

Table 4. *Elemental composition.*

	Element	Fe	Ti	Si	Zr	Al	Ca	Mn	Mg
[%]	Initial sample	58.02	18.40	12.40	4.58	1.65	1.12	0.98	0.68
	Concentrate	90.08	4.33	0.40	ND	1.52	0.20	0.19	0.31

Figure 4. *X-ray diffraction spectra for the initial waste and concentrate.*



The XRF analysis revealed that the initial sample exhibited a composition of 58.02% iron (Fe), 18.40% titanium (Ti), and 12.40% silicon (Si), with minor impurities of zirconium (Zr), aluminum (Al), calcium (Ca), manganese (Mn), and magnesium (Mg). Following the magnetic separation process, the concentration of iron (Fe) increased significantly, reaching 90.08%. In contrast, the concentrations of impurities, including titanium (Ti) and silicon (Si), decreased to 4.33% and 0.40%, respectively. This resulted in a concentrate of higher purity (see Table 4).

X-ray diffraction (XRD) analysis revealed that the initial sample was primarily composed of ilmenite (42%), quartz (30%), magnetite (14%), and zircon (14%). Following the concentration process, magnetite became the predominant phase, representing 73% of the total, while the proportion of ilmenite decreased to 27%. This corroborates the efficacy of the magnetic concentration process in obtaining minerals with high purity magnetic properties (see Figure 4).

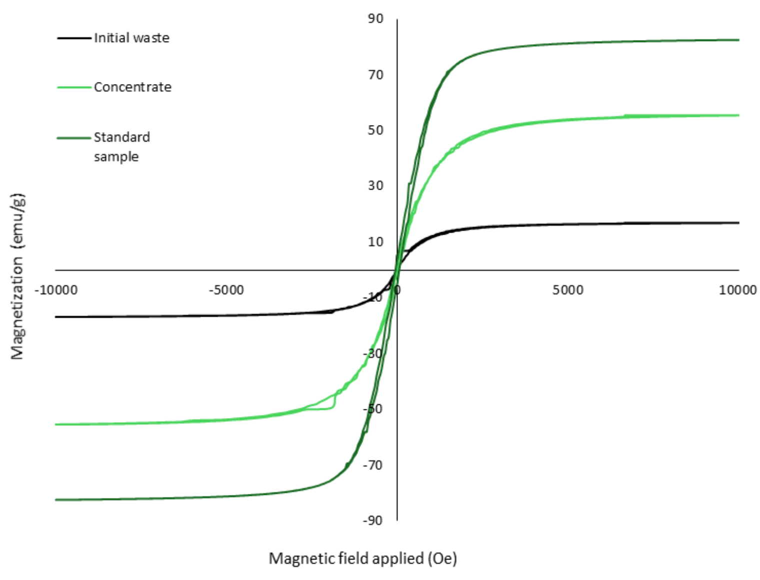
The magnetite is presented in its cubic phase with lattice parameters a, b, and c = 8.3941 Å and angles α, β, and γ = 90°. It exhibits a characteristic peak at 2Θ = 35.4°, corresponding to the (311) plane according to Miller indices. In contrast, ilmenite, in

Revista EIA https://doi.org/10.24050/reia.v22i44.1851

its rhombohedral crystal system, exhibits the following lattice parameters: a = 5.0870 Å, b = 5.0870 Å, and c = 14.0420 Å. The main peak is observed at 2ϴ = 32.5°, corresponding to the (104) plane.

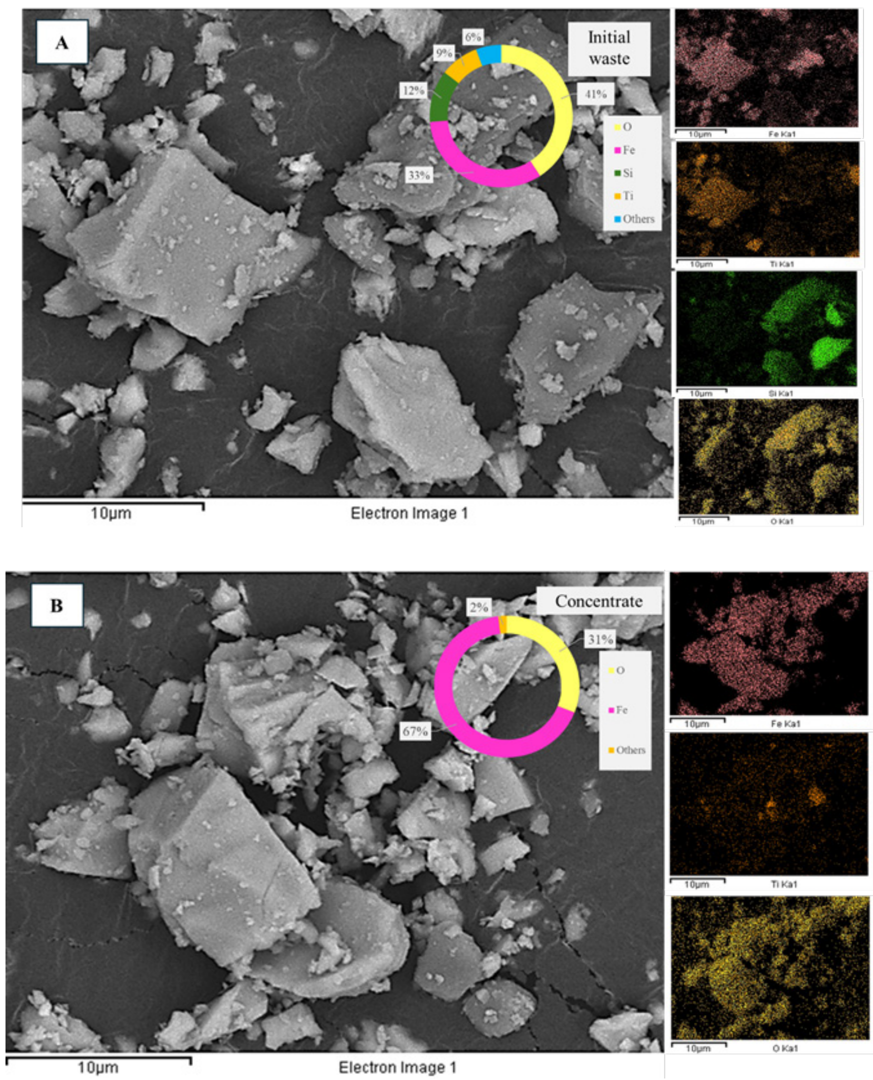
Figure 5 illustrates the magnetic response of three samples: the initial waste of black sands supplied for Mineros Aluvial S.A., the concentrate obtained after magnetic separation of initial waste, and the magnetization curve of magnetite nanoparticles supplied by Merck at 97% purity as a standard sample. Following the concentration process, a significant increase in saturation magnetization is observed in the concentrate, compared to the initial waste from 16.73 emu/g to 55.34 emu/g, which represents a 47% variation with respect to the standard sample. This reflects the removal of a considerable portion of the non-magnetic impurities, including silicon (Si) and titanium (Ti), which were previously identified in the XRF analysis. This indicates that the magnetic separation process was effective in concentrating for the magnetite, a highly magnetic mineral, whose saturation magnetization for the pure sample is 82.46 emu/g.

Figure 5. *Magnetization curves*



Although the increase in magnetization of the original waste when passing through magnetic separation is substantial, the presence of ilmenite (a weakly magnetic mineral) in the concentrate reduces the overall magnetic response, as evidenced in the magnetization curve of the concentrate. This behavior is consistent with the XRD results, which indicate that ilmenite, which was present at 42% in the initial sample, was reduced to 27% in the concentrate. While ilmenite exhibits a slight magnetization, its contribution is significantly lower compared to magnetite, which explains the behavior in the magnetization curves between the concentrate and pure magnetite.

Figure 6. *SEM -EDS images for A) initial waste and B) concentrate*



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As illustrated in the SEM-EDS images (see Figure 6), the mineral sample is observed both before and after the concentration process. The elemental mapping demonstrates a notable elevation in the concentrations of Fe and O elements subsequent to the concentration process. This finding aligns with the XRF results, which indicate an increase in the proportion of iron in the concentrated sample (90.08% Fe) in comparison to the initial sample (58.02%). Aditionally, a diminution in non-magnetic elements, including titanium (Ti) and silicon (Si), is observed, which is also consistent with the reduction of these elements in the composition obtained by XRF.

The SEM-EDS images indicate that the residual presence of Ti is likely due to the limitations of the magnetic separation equipment, as ilmenite continues to respond, albeit weakly, to the applied magnetic field. To further enhance the concentrate's purity, it would be prudent to optimize the process by implementing a magnetic field of reduced intensity. This approach would facilitate the continued efficient separation of magnetite while preventing ilmenite from responding to the field, thereby enhancing both the concentrate's purity and its magnetization.

The concentration of magnetite in the samples analyzed increased from 14% to 73% after the magnetic separation process, which was reflected in a remarkable improvement in saturation magnetization from 16.73 emu/g to 55.34 emu/g. This high purity and magnetic response highlight the potential of these wastes for energy applications through the formulation of ferrofluids. However, to optimize the performance of these ferrofluids, advanced size reduction methods such as high-energy milling or laser ablation must be implemented to reach the nanometer or sub-micrometer scale.

4. Conclusions

The study has demonstrated that mining waste from the municipality of El Bagre, situated within the lower Cauca region of Antioquia, represents a viable source for the production of magnetic nanoparticles with energy applications, particularly for the formulation of ferrofluids. The identification of black sands rich in magnetite allows for the utilization of these wastes, thereby promoting the circular economy and the sustainable use of resources.

Following the magnetic separation process, the magnetite content of the sample was increased to 73%, as evidenced by XRD and SEM-EDS analysis. This increase in the purity of the magnetite concentrate is consistent with the XRF results, which demonstrated a significant increase in iron (from 58% to 90%) in the concentrated sample, while impurities such as silicon and titanium exhibited a marked decline.

Although the saturation magnetization of the concentrate increased significantly (from 16.73 emu/g to 55.34 emu/g), the residual presence of ilmenite, a weakly magnetic mineral, affected the overall magnetic response. To further optimize the purity of the concentrate, it is recommended that the magnetic field strength in the separation process be adjusted in order to maximize the extraction of magnetite and minimize the presence of ilmenite.

The findings illustrate that mining byproducts from El Bagre can not only be utilized for the extraction of valuable materials but also have the potential to contribute to the development of more efficient technologies, such as ferrofluids for thermal applications. This supports the pursuit of a more sustainable energy transition.

5. References

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