International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Evaluation of Gravity-Based Separation Techniques in the Beneficiation of Chromite Ores

Dr. Zehra Çetinkaya

Lecturer Dr.
Cukurova University, Central Research Laboratory, Adana, Türkiye

Abstract

Chromite is a critical industrial mineral used in the production of ferrochrome, which serves as the primary alloying material in stainless steel manufacturing, due to its chemical composition and physical properties. Natural chromite ores vary in terms of mineral associations, particle size distributions, and Cr_2O_3 content, which directly influence their beneficiation strategies. The growing global demand for high-grade chromite concentrates has intensified the need for effective separation methods. Gravity-based separation is widely applied for chromite beneficiation due to the significant specific gravity difference between chromite and gangue minerals. Key factors that determine the choice of beneficiation method include the ore's particle size, degree of liberation, chromite content, and the nature of associated gangue materials. In addition to gravity separation, techniques such as magnetic separation, flotation, and roasting-leaching combinations may also be employed depending on the mineralogical characteristics of the ore. In this study, the efficiency of both conventional (jig, shaking table, spiral concentrator) and advanced gravity separation devices (MGS, Knelson, Falcon) is evaluated to highlight their potential roles in chromite beneficiation.

Keywords: Chromite ore, Gravity separation, Gangue minerals, Liberation degree, Beneficiation

1. Introduction

Chromite is essential for producing high carbon ferrochrome, which is predominantly used in stainless steel manufacturing (Basson and Daavittila, 2013). Beyond stainless steel, chromite is also utilized in nickel-chromium alloys and various nonferrous alloys, enhancing their corrosion and heat resistance (Vasilescu and Dobrescu, 2019). As the primary source of chromium, chromite ($FeCr_2O_4$) is usually found in complex ore matrices composed of silicate and oxide gangue minerals (Pownceby et al., 2023; Sánchez-Ramos et al., 2008). In its raw form, chromite ore generally does not contain sufficient Cr_2O_3 levels, making beneficiation essential to upgrade the chromium content (Singh et al., 2014). The beneficiation of chromite is predominantly carried out using gravity-based methods due to the considerable specific gravity difference between chromite and associated gangue minerals. The choice of beneficiation technique largely depends on the degree of mineral liberation and the physical and chemical characteristics of both the ore and gangue phases (Pownceby et al., 2023). Mineral liberation, the extent to which chromite is freed from the gangue matrix, is a critical factor in determining processing efficiency (Maruli and Nheta, 2020). This study provides a comprehensive overview of the mineralogical characteristics, global reserves, and industrial applications of chromite. In particular, it focuses on gravity-based separation techniques and evaluates their efficiency in the beneficiation of chromite ores under varying mineralogical conditions.

2. General Information

2.1. Properties of Chromium

Chromite, known as "chrome ore," is the sole mineral source of commercially extractable chromium (Zhang et al., 2019; Mishra et al., 2019). The percentages of SiO_2, Cr_2O_3, and Al_2O_3 in chromite ore, along with the Cr/Fe ratio, play a crucial role in determining its potential applications. In nature, the highest known Cr_2O_3 content in chromite reaches up to 68%. For ferrochrome production, chromite ore with a Cr_2O_3/FeO ratio between 2.5 and 3.0 is preferred. Low-grade ores with Al_2O_3 content above 15% are used in the manufacturing of heat-resistant refractories. In ores intended for refractory production, the Cr/Fe ratio is not considered critical. However, in addition to a high Al_2O_3 content, the SiO_2 level should not exceed 4–6%, while sulfur and phosphorus contents must remain below 0.05% and 0.07%, respectively (Yıldız, 2014).

2.2. Modes of Chromite Formation

Chromium is commercially obtained exclusively from chromite, commonly known as chrome ore (Zhang et al., 2019; Mishra et al., 2019). This mineral is predominantly associated with ultrabasic igneous rocks, including peridotite, serpentinite, pyroxenite, and dunite. Economically significant chromite occurrences are generally classified into two primary deposit types: stratiform and podiform. Chromite crystals in podiform deposits are coarse and characterized by low iron and titanium content, while chromium, aluminum, and magnesium levels are high. Stratiform deposits, which account for approximately 90% of the world's chromite reserves, contain fine-grained chromite crystals with high iron content and lower aluminum and magnesium concentrations (Yıldız, 2014; Vasilescu and Dobrescu, 2019).

2.3. Applications of Chromium

Chromite ore is primarily used in the metallurgical, chemical, refractory, and foundry industries. The chemical composition and physical properties of the ore can impose certain limitations on its industrial applications. In particular, the contents of SiO_2, Cr_2O_3, and Al_2O_3, as well as the Cr/Fe ratio determined through chemical analysis, are critical parameters that significantly influence its suitability for various uses. Classifications of chromite ores produced in Turkey, based on their chemical composition and industrial applications, are presented in Table 1 (State Planning Organization (Türkiye) (SPO), 2001).

Table 1: Classification of chromite ores produced in Turkey based on their areas of application (SPO, 2001).

Sector	Component	Content	Specification
A) Metallurgy	a) Cr_2O_3	34–40%	Cr/Fe > 2.5, lump ore
	b) Cr_2O_3	> 40%	Cr/Fe > 2.0, lump ore
	c) Cr_2O_3	46–48%	Cr/Fe > 2.6, concentrate
	d) Cr_2O_3	> 36%	-25 mm, washed

B) Chemical	Cr_2O_3	> 40%	Cr/Fe > 1.5, concentrate
C) Refractory	Cr_2O_3	> 48%	SiO_2 < 4%, lump ore
	$Cr_2O_3 + Al_2O_3$	> 60%	SiO_2 < 4%, lump ore
	Cr_2O_3	> 46%	SiO_2 < 1%, concentrate
	Cr_2O_3	> 50%	SiO_2 < 2%, concentrate
D) Foundry Sand	Cr_2O_3	> 44%	SiO_2 < 4%
	Fe_2O_3	< 26%	CaO < 0.5%, concentrate

2.4. Chromite Reserves in the World and in Türkiye

A significant portion (96%) of the world's known chromite reserves, estimated at 3.6 billion tons, is located within the borders of South Africa, Zimbabwe, and Kazakhstan. South Africa alone accounts for approximately 84% of the global reserves. Türkiye's chromite reserves, on the other hand, represent about 0.2% of the world total. Although Türkiye is not a leading country in terms of reserve size, it holds a prominent position globally due to the high quality of its chromite ore. The ore produced from Türkiye chromite deposits commands higher prices on the international market compared to ores of similar grade elsewhere. This is primarily due to its superior metallurgical properties (Fırat Development Agency, 2020). Chromite deposits in Türkiye can be classified into six distinct regions: Guleman, Sivas-Erzincan-Kop Mountain, Fethiye-Köyceğiz-Denizli, Mersin-Adana-Kayseri, Bursa-Kütahya-Eskişehir, and İskenderun-Gaziantep regions (General Directorate of Mineral Research and Exploration (MTA), 2022). In terms of global chromite reserves, Türkiye ranks fourth after South Africa, Kazakhstan, and India. Chromite reserves by country for the year 2023 are presented in Figure 1 (Republic of Türkiye Ministry of Energy and Natural Resources, 2024).

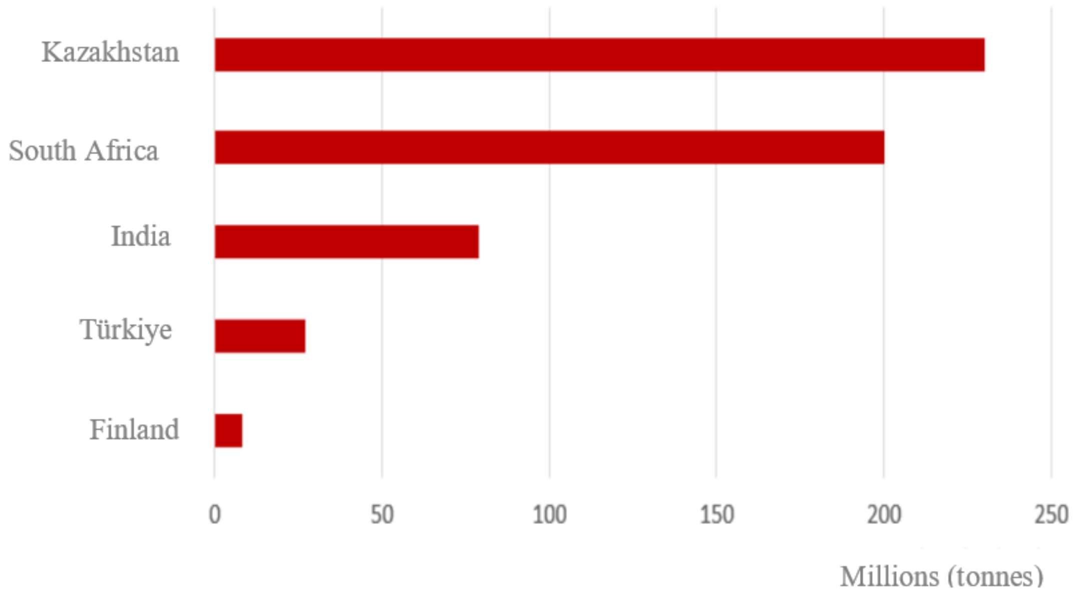

Figure 1: Chromite reserves by country in 2023 (Republic of Türkiye Ministry of Energy and Natural Resources, 2024).

2.5. Chromite Production in Türkiye

Türkiye is one of the important countries in chrome production. Its major competitors in the global market include South Africa, Kazakhstan, and India. Turkish chromite ores offer several market advantages: they are easily reducible by carbon, resulting in high metal recovery rates; they can be used directly in ferrochrome production without prior beneficiation; their low silica content enables the production of high-quality ferrochrome (FeCr); their high Cr/Fe ratio allows for the extraction of high-grade metal; their hardness leads to less dust generation; and the slag produced during processing is easier to handle. Turkey's chromite ore production increased by 19% in 2022 compared to the previous year, reaching approximately 8.28 million tons. In 2023, however, production declined by 1.5%, totaling 8.16 million tons (Figure 2) (Republic of Türkiye Ministry of Energy and Natural Resources, 2024).

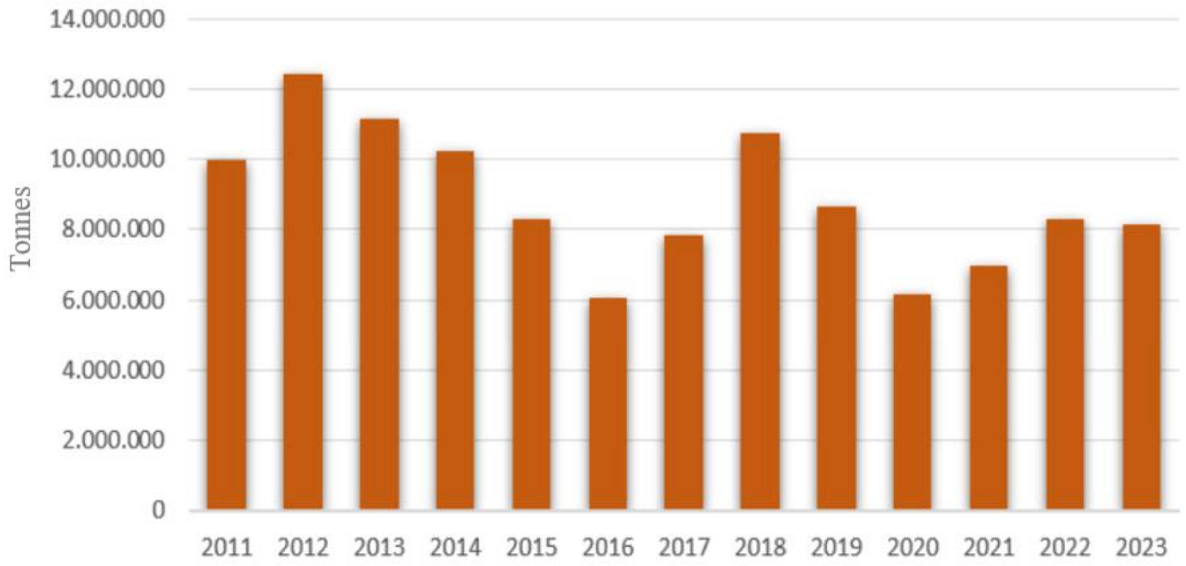

Figure 2: Türkiye's run-of-mine chromite ore production (2011–2023) (Republic of Türkiye Ministry of Energy and Natural Resources, 2024).

3. Chromite Beneficiation Using Gravity Separation

Chromite deposits can consist of both low-grade and high-grade ores. Ores with less than 40% Cr_2O_3 are classified as low-grade, those containing 40–46% Cr_2O_3 are considered medium-grade (second-grade), and those with more than 46% Cr_2O_3 are regarded as high-grade (first-grade). High-grade chromite ores can be used directly in industry without beneficiation, whereas low-grade ores must be upgraded to meet industrial specifications (Tabazık and Öztürk, 2019).

Chromite beneficiation aims to increase Cr_2O_3 content while reducing impurities (Maulik and Bhattacharyya, 2005). Common beneficiation methods for chromite include gravity separation, magnetic separation, and flotation (Tabazık and Öztürk, 2019). Chromite ore is generally beneficiated by gravity separation due to its high specific gravity. This method takes advantage of the significant difference in specific gravity between chromite (4.1–4.9 g/cm^3) and gangue minerals such as serpentine (2.6 g/cm^3 and olivine (3.2–4.0 g/cm^3) (Yıldız, 2014). Gravity separation is preferred due to its low operating costs, ease of use, and environmentally friendly characteristics. However, its efficiency strongly depends on factors such as particle size, degree of liberation, and ore texture (Izerdem and Ergun, 2024). Gravity separation equipment employed in chromite beneficiation includes classical devices such as jigs, shaking tables, and spiral concentrators; centrifugal concentrators such as Falcon and Knelson; and advanced fine-particle separators like the Multi-Gravity Separator (MGS).

3.1. Beneficiation Using Jigging

In the jigging process, periodic water pulses fluidize the particle bed, leading to stratification governed by particle size and specific gravity (SG). The stratified layers are then selectively removed (Nzeh et al., 2023). For efficient jigging, chromite particles must be liberated at relatively coarse sizes. Ores in the size range of 25–1 mm can be concentrated using hydraulic jigs, while in air jigs the lower particle size limit extends down to 0.1 mm. To enhance the efficiency of separation, classification into narrow size fractions is carried out (Gence, 1985).

The effectiveness of jigging in chromite beneficiation has been demonstrated in several studies. For instance, in chromite ore from the Tokat region, the −3.35 + 2 mm fraction was treated using a laboratory jig, producing a concentrate containing 38.35% Cr_2O_3 with 92.04% recovery. Despite achieving a high recovery, the concentrate was considered to require further upgrading since its grade showed only a slight improvement over the feed (Aras and Taner, 2023). A recent study has focused on the integration of intelligent control systems into jigging processes. Shiryayeva et al. (2025) developed a hybrid model combining physical simulation, regression, and artificial neural networks to optimize jigging parameters for fine chromite ores. Their results demonstrated that real-time control could reduce chromium losses in tailings and improve concentrate quality, highlighting the potential of digitalized and sustainable jigging operations.

3.2. Beneficiation Using Shaking Table

Shaking tables are devices commonly used for the gravity concentration of chromite ores. Essentially, a shaking table consists of a rectangular, trapezoidal, or V-shaped deck surface over which a thin layer of slurry flows. By means of an appropriate mechanism, the table is moved back and forth along its longitudinal axis, with the return stroke being faster than the forward motion (Gence, 1985). In shaking tables, the surface is tilted and fitted with riffles, which provide the conditions required for hindered settling (Gupta and Yan, 2016).

The efficiency of shaking tables has been demonstrated in several beneficiation studies. Can et al. (2019) investigated the beneficiation of a very low-grade chromite ore. They reported that a final concentrate corresponding to 6.8% by weight with 49.5% Cr_2O_3 grade and 71.51% recovery was obtained using a flowsheet of spiral concentrators, teetered bed separator (TBS), and shaking tables. In a recent study on the South African MG2 chromite seam, shaking table tests successfully upgraded the ore from 18.18% Cr_2O_3 to 42.0% Cr_2O_3, achieving high recoveries (Sixhuta et al., 2024). Kaseba and Nheta (2024) achieved a concentrate grading 36.97% Cr_2O_3 with 71.59% recovery from the -106 + 53 µm size fraction under optimized shaking table conditions. In a study on UG-2 tailings, shaking table tests achieved a maximum recovery of 67.27% Cr_2O_3 at a concentrate grade of 21.87% Cr_2O_3. Multiple linear regression analysis provided good prediction for recovery ($R^2 = 0.66$) but poor prediction for grade ($R^2 = 0.18$), indicating that the equations could be used to predict chromite recovery from UG-2 tailings (Manala and Nheta, 2024). These findings indicate that shaking tables continue to be a versatile and effective technique for chromite beneficiation, particularly across a wide range of ore grades and particle sizes.

3.3. Beneficiation Using Spiral Concentrator

The spiral concentrator is essentially a sluice with a helical shape, along which the flowing pulp follows a circular path. Under the combined influence of centrifugal force and gravity, the feed pulp spreads across the spiral surface. Heavier particles tend to settle toward the spiral's surface, whereas lighter particles remain suspended and are carried outward. The Humphrey spiral, introduced by Humphrey in 1943, was first applied commercially in the beneficiation of chromite (Goodman et al., 1985; Acarkan and Önal, 2014). These concentrators are characterized by their simplicity, efficiency, ease of operation, low maintenance requirements, and relatively low capital and operating costs (Gupta and Yan, 2016; Malekabadi, 2022).

Their potential effectiveness has been highlighted in several studies. For instance, Maulik and Bhattacharyya (2005) investigated the beneficiation of low-grade chromite ores from the Sukinda region and demonstrated that spiral concentrators alone could produce concentrates with Cr_2O_3 grades of about 42%, indicating their effectiveness in treating such ores. In beneficiation tests on plant tailings using a spiral concentrator, Bilici (2018) achieved the best results at the −600 µm particle size fraction, obtaining a Cr_2O_3 grade of 14.90% with a recovery of 81.30%. In a study on Tokat chromite ore, Aras and Taner (2023) reported that beneficiation experiments with spiral concentrators yielded concentrates of 39.31% Cr_2O_3 at 43.87% recovery for the –2+1 mm size fraction and 45.10% Cr_2O_3 at 71.56% recovery for the –1+0.5 mm size fraction, indicating better performance at finer sizes.

3.4. Beneficiation Using Multi Gravity Separator

The Multi-Gravity Separator (MGS) operates by feeding a pulp of suitable solid concentration under pressure onto the inner surface of a rotating drum. This design reduces turbulence during feeding, thereby allowing effective stratification. Wash water is introduced near the upper discharge end of the drum to assist in separation. Under the combined action of centrifugal force and vibration, heavy minerals with higher specific gravity settle onto the drum surface, forming a dense layer, while lighter particles remain in the fluidized layer (Yıldırım et al., 1995). Specially designed scrapers gradually move the stratified material upward along the drum surface, discharging the heavy particles through the upper outlet as a concentrate. The lighter minerals, on the other hand, are conveyed by the wash water to the lower outlet, where they are discharged as tailings (Chan et al., 1991; Deniz, 2019).

An MGS is a gravity concentrator manufactured for the beneficiation of fine and very fine mineral particles and used in the industry (Aras & Taner, 2023). This device has been the subject of several studies. For instance, Eskibalcı et al. (2002) investigated the beneficiation of chromite wastes from a concentrator in the Kavak region using an MGS. The feed sample contained 18.74% Cr_2O_3, and the tests produced a concentrate grading 47% Cr_2O_3 with a recovery of 64.42%, demonstrating the potential of the MGS for upgrading such low-grade wastes. Another study by Özgen et al. (2012) investigated the combined application of a multi-gravity separator and hydrocyclone for fine chromite tailings, reporting that this configuration yielded improved Cr_2O_3 grade and recovery by effectively separating ultrafine particles which are typically lost in conventional gravity methods. In experiments conducted with an MGS using chromite tailings containing 23.84% Cr_2O_3, Deniz (2019) obtained a concentrate grading 41.72% Cr_2O_3 with a recovery of 81.34%. These findings collectively demonstrate that the MGS is a versatile and efficient separator for the beneficiation of fine and ultrafine chromite tailings, offering a valuable alternative where conventional gravity methods are less effective.

3.5. Beneficiation Using Knelson Gravity Concentrator

The Knelson Gravity Concentrator (KC) is a high-speed centrifugal separator patented by Byron Knelson in Canada in 1988. The standard Knelson concentrator can treat feed material with a top size of 6 mm or less (Patchejieff et al., 1995). Its simple design, high capacity, ability to handle a broad particle size range, and capability to achieve very high enrichment ratios are regarded as its key advantages (Bozkurt, 2017).

The KC is highly effective in separating fine and ultrafine heavy minerals from lighter minerals by applying centrifugal force, which can reach values of up to 60 g. At such high centrifugal fields, progressively finer particles can be recovered. The unit consists of a high-speed rotating bowl into which slurry is fed through a vertical tube. Under centrifugal action, heavy particles are retained in the grooves of the bowl, while lighter minerals are discharged with the overflow. The feed pulp density can vary between 0 and 70% (Knelson & Jones, 1994). Wash water is injected through small perforations in the parallel grooves of the bowl, which both washes the material and assists in the retention of heavy particles within the grooves (Zhang 1998).

The effectiveness of the KC in chromite recovery has also been demonstrated by Bozkurt (2017), who investigated shaking table tailings containing 2.28% Cr_2O_3. For the −212 µm fraction, the best results were obtained at 90 g and 8 psi, yielding a pre-concentrate with 21.5% Cr_2O_3 grade and 73.18% recovery, confirming its potential for upgrading low-grade chromite wastes.

3.6. Beneficiation Using Falcon Gravity Concentrator

The Falcon concentrator is designed to separate minerals of varying specific gravities by employing a high-intensity centrifugal field. The material, in the form of slurry, is fed into a rapidly rotating rotor mechanism. The feed then enters the concentration zone, where high-density minerals accumulate while lighter minerals are carried outward with water. The concentrate adhering to the rotor wall is collected at specific intervals, either manually or automatically, once the unit is stopped. The design of the Falcon concentrator is simple, with few moving parts, which makes it easy to maintain. The wear-prone areas are lined with rubber to minimize abrasion. The Falcon concentrator is capable of generating centrifugal forces of up to 300 g (Önel, 2011).

The efficiency of the Falcon concentrator in chromite processing has also been demonstrated in several studies. Rath et al. (2017) investigated the recovery potential of chromite beneficiation plant tailings from Odisha Mining Co. using an SB-40 type Falcon gravity concentrator. The tailings contained 20.23% Cr_2O_3, with 68% of the material finer than 11 µm. Experiments showed that increasing the frequency of the rotation bowl (20–80 Hz) decreased the concentrate grade but increased the chromite recovery. Conversely, increasing the back water flow rate (1–15 psi) improved the Cr_2O_3 grade but lowered the recovery. Under optimal conditions, a concentrate grading 41.71% Cr_2O_3 with a recovery of 68.2% was obtained. Bilici (2018) investigated the recovery of chromite from Sivas-Kangal-Çamözü plant tailings assaying 4.95% Cr_2O_3 using various methods, including the Falcon concentrator. With a −150 µm feed size, at 20 g rotor speed and 40 kPa water pressure, the Falcon concentrator produced a concentrate grading over 15% Cr_2O_3 with 81.30% recovery, highlighting its potential for upgrading low-grade chromite tailings.

4. Conclusions

Gravity-based separation techniques remain among the most effective and widely applied methods for chromite beneficiation. The selection of a specific device can be made by considering ore characteristics, mineral liberation, desired grade recovery balance, and plant capacity. Each unit offers distinct advantages within certain particle size ranges jigs for coarse fractions, shaking tables and spirals for intermediate sizes, and centrifugal devices such as MGS, Knelson, and Falcon for fine to ultrafine particles. In practice, the best performance can often be achieved by integrating multiple gravity units in a flowsheet, supported by appropriate classification and desliming.

References

1. Acarkan, N., & Önal, G. (2014). Beneficiation by gravity concentration. In: Önal, G., Ateşok, G., & Perek, K. T. (Eds.), Mineral Processing Handbook (pp. 127–159). YMGV.
2. Aras, A., & Taner, H. A. (2023). Investigation of chromite ore beneficiation possibilities with different gravity concentrators. Rudarsko-geološko-naftni zbornik, 38(2), 127-134.
3. Basson, J., & Daavittila, J. (2013). Handbook of Ferroalloys: Chapter 9. High Carbon Ferrochrome Technology. Elsevier Inc. Chapters.
4. Bilici, E. (2018). Studies on the recovery of Sivas-Kangal Çamözü chromite beneficiation plant tailings (Master's thesis). Inonu University, Graduate School of Natural and Applied Sciences, Department of Mining Engineering, Malatya, Turkey. [In Turkish, with English abstract].
5. Bozkurt, B. (2017). The impact of Knelson gravity concentrator on recovery of chromium from enrichment plant wastes (Master's thesis). Afyon Kocatepe University, Graduate School of Natural and Applied Sciences, Department of Mining Engineering, Afyon, 50 p. (in Turkish, with English abstract)
6. Can, İ. B., Özsoy, B., & Ergün, S. L. (2019). Developing an optimum beneficiation route for a low-grade chromite ore. Physicochemical Problems of Mineral Processing, 55(4), 865-878.
7. Chan, B. S. K., Mozley, R. H., & Childs, G. J. C. (1991). Extended trials with the high tonnage multi-gravity separator. Minerals Engineering, 4(3–4), 489–496.
8. Deniz, V. (2019). Evaluation by multi gravity separator (MGS) of a low grade chromite tailing from Yeşilova-Burdur (Turkey). Inżynieria Mineralna, 1(1), 101–106.
9. Eskibalcı, F., Çinku, K., Kurşun, İ., & Özkan, Ş. G. (2002). Concentration of chromite wastes from the Kavak region by using multi-gravity separator. Istanbul Journal of Earth Sciences, 15(2), 55–62.
10. Fırat Development Agency. (2020). Pre-feasibility Report of High-Carbon Ferrochrome Production Plant in Elazığ Province. Malatya, p. 48.
11. Gence, N. (1985). Beneficiation of Elazığ Kafdağı Chromites. M.Sc. Thesis, Institute of Science, Anadolu University, Eskişehir, Turkey.
12. General Directorate of Mineral Research and Exploration (MTA). (2022). Chromite deposits of Turkey [Map]. Retrieved from https://www.mta.gov.tr/v3.0/sayfalar/hizmetler/images/b_h/krom.jpg (Accessed: August 2025).
13. Goodman, R. H., Brown, C. A., & Ritchie, I. C. (1985). Advanced gravity concentrators for improving metallurgical performance. Mining, Metallurgy & Exploration, 2(2), 79–86.
14. Gupta, A. and Yan, D. (2016): Gravity Separation. In: Gupta, A. and Yan, D. (eds.): Mineral Processing Design and Operations. Elsevier, 563-628, 850 p.

15. Izerdem, D., & Ergun, S. L. (2024). Investigation of the effects of particle size on the performance of classical gravity concentration equipment. Mineral Processing and Extractive Metallurgy Review, 45(3), 155-172.
16. Kaseba, C. N. Y. L., & Nheta, W. (2024). Application of Response Surface Methodology on the Optimization of Chromite Recovery from the South African Middle Group Chromite Seams. Journal of Sustainable Metallurgy, 10, 929-949.
17. Knelson, B., & Jones, R. (1994). "A new generation of Knelson concentrators" a totally secure system goes on line. Minerals Engineering, 7(2-3), 201-207.
18. Malekabadi, H., 2022. Investigation of the ability of chrome concentrate from chrome enrichment plant wastes. MSc thesis, Eskişehir Technical University, Institute of Graduate Programs, Department of Advanced Technologies, Eskişehir. [In Turkish, with English abstract].
19. Manala, K., & Nheta, W. (2024). Application of multiple linear regression (MLR) analysis on the concentration of chromite plant tailings by a shaking table. Proceedings of the 10th World Congress on Mechanical, Chemical, and Material Engineering (MCM'24), Barcelona, Spain, August 22–24, 2024. Paper No. MMME 117.
20. Maruli, M., & Nheta, W. (2020). Liberation analysis of South African Middle group seam chromite ore processed with Vertical Shaft Impactor Crusher. Proceedings of the 6th World Congress on Mechanical, Chemical, and Material Engineering, 1-7. Article MMME 135.
21. Maulik, S. C., & Bhattacharyya, K. K. (2005) Beneficiation of Low Grade Chromite Ores from Sukinda. In: International Seminar on Mineral Processing Technology (MPT-2005), (pp. 146–154). Dhanbad, India, January 6–8, 2005.
22. Mishra, U., Chandroth, A., Basantaray, A. K., Chel, S., & Mandal, A. (2019). Assessing chromite ore processing residue (COPR) waste dump site using electrical resistivity tomography (ERT): a case study from Umaran, Kanpur, India. Environmental monitoring and assessment, 191: 504.
23. Nzeh, N. S., Popoola, P., Okanigbe, D., Adeosun, S., & Adeleke, A. (2023). Physical beneficiation of heavy minerals–Part 1: A state of the art literature review on gravity concentration techniques. Heliyon, 9(8).
24. Önel, Ö. (2011). Gravity-based processing methods used in the enrichment of gold ore and a case study. M.Sc. Thesis, Dokuz Eylül University, Izmir, Turkey.
25. Özgen, S. (2012). Clean chromite production from fine chromite tailings by combination of multi gravity separator and hydrocyclone. Separation Science and Technology, 47(13), 1948–1956.
26. Patchejieff, B., Gaidarjiev, S., & Lazarov, D. (1995). Opportunities for fine gold recovery from a copper flotation circuit using a Knelson concentrator. Minerals Engineering, 7(2–3), 405–409.
27. Pownceby, M. I., McCallum, D. A., & Bruckard, W. J. (2023). Automated and quantitative mineralogy applied to chromite ore characterization and beneficiation. Minerals, 13(3), 440.
28. Rath, R. K., Dey, B., Mohanta, M. K., Prusty, L. K., & Singh, R. (2017). Recovery of chromite values from tailings of COB plant using enhanced gravity concentrator. Paper presented at the International Conference on Mineral Processing Technology (MPT), Indian Institute of Mineral Engineers, Chennai, India, February 1–3.
29. Republic of Türkiye Ministry of Energy and Natural Resources. (2024). Chromite. Retrieved from https://enerji.gov.tr/bilgimerkezi-tabiikaynaklar-krom (Accessed: July 16, 2025).

30. Sánchez-Ramos, S., Doménech-Carbó, A., Gimeno-Adelantado, J. V., & Peris-Vicente, J. (2008). Analytical and mineralogical studies of ore and impurities from a chromite mineral using X-ray analysis, electrochemical and microscopy techniques. Talanta, 74(5), 1592-1597.
31. Shiryayeva, O., Suleimenov, B., & Kulakova, Y. (2025). Sustainable Mineral Processing Technologies Using Hybrid Intelligent Algorithms. Technologies, 13, 269.
32. Singh, R. K., Dey, S., Mohanta, M. K., & Das, A. (2014). Enhancing the utilization potential of a low grade chromite ore through extensive physical separation. Separation Science and Technology, 49(12), 1937-1945.
33. Sixhuta, I., Singh, A., Khangale, P., Meijboom, R., & Raphulu, M. (2024). Characterization and Processing of Low-Grade Middle Group 2 Chromite Ore by Gravity Shaking Table and a Comparative SLon Magnetic Separation: A Case Study. Minerals, 14, 1201.
34. State Planning Organization (SPO). (2001). Mining Special Expertise Commission Report: Sub-commission on Metallic Minerals, Chromite Working Group Report. Eighth Five-Year Development Plan (DPT: 2626 – ÖİK: 637). Ankara: State Planning Organization.
35. Tabazık, T., & Öztürk, F. D. (2019). Investigation of beneficiation of Aladağ (Adana) chromite ore using the Taguchi method. Dicle University Journal of Engineering, 10(1), 229–237.
36. Vasilescu, M., & Dobrescu, M. (2019). Chromite. Processing and Applications. The Annals of "Dunarea de Jos" University of Galati. Fascicle IX, Metallurgy and Materials Science, 42(1), 12-18.
37. Yıldırım, İ., Ateşok, G., & Çelik, M. (1995). Production of ultra-low ash coal from coal–water mixtures using a laboratory–pilot scale multi-gravity separator. In Proceedings of the 14th Mining Congress of Turkey (pp. 443–448). Ankara: ISBN 975-395-150-7.
38. Yıldız, N. (2014). Ore Preparation and Beneficiation. Ertem Publishing.
39. Zhang, B. (1998). Recovering gold from high density gangues with Knelson concentrator (Master's thesis). McGill University, Montreal, Canada.
40. Zhang, W., Zhang, P., Liu, F., Liu, W., Zhang, J., & Lin, Z. (2019). Simultaneous oxidation of Cr (III) and extraction of Cr (VI) from chromite ore processing residue by silicate-assisted hydrothermal treatment. Chemical Engineering Journal, 371, 565-574.