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A Review of Chromite Residues Secondary Raw Material Potential in Türkiye

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ABSTRACT

Chromium production is widespread globally and effective management of its waste materials is critically important due to the significant environmental and health risks posed by improper disposal. Türkiye, with around 2,000 active chromite deposits, is one of the leading chromium producers in worldwide. Chromite is primarily used in the metallurgy, chemical, and refractory industries, and its resistance to corrosion makes it valuable in the automotive, aerospace, and machinery sectors. Its enrichment in platinum group elements (PGEs)—such as osmium, ruthenium, iridium, rhodium, palladium, and platinum —adds further economic value, as do associated minerals like olivine and serpentine commonly found in chromite deposits. Despite its economic potential, improper handling of chrome ore residues presents serious environmental threats, including water and soil contamination and air pollution. These issues are often worsened by the presence of toxic heavy metals, including PGEs. To mitigate these impacts, there is growing interest in utilizing chrome residues as secondary raw materials. Recovering valuable components from these wastes not only reduces environmental hazards but also contributes to more sustainable resource use. This study reviews both global and local efforts aimed at reclaiming chromium from mining residues. It highlights the importance of developing efficient recovery processes and expanding their application across Türkiye. Promoting such practices is essential for environmental protection and offers considerable economic benefits. The main goal is to support the advancement of sustainable chromium recovery, ensuring both ecological preservation and improved resource efficiency.

Keywords: Heavy metal, Chrome ore, Chromium recovery, Platinum Group Elements (PGEs), Mining residues management, Environmental sustainability

Türkiye Kromit Artıklarının İkincil Hammadde Olma Potansiyelinin Değerlendirilmesi

ÖZ

Krom üretimi dünya genelinde yaygın olarak gerçekleştirilmektedir ve bu süreçte ortaya çıkan atıkların etkin bir şekilde yönetilmesi, uygunsuz bertarafın neden olduğu ciddi çevresel ve sağlık riskleri nedeniyle hayati önem taşımaktadır. Yaklaşık 2.000 aktif kromit yatağıyla Türkiye, dünya genelinde önde gelen krom üreticilerinden biridir. Kromit cevheri başta metalürji, kimya ve refrakter sanayilerinde kullanılmakta olup, korozyona karşı yüksek direnci sayesinde otomotiv, havacılık ve makine sektörlerinde de büyük bir öneme sahiptir. Ayrıca, osmiyum, rutenyum, iridyum, rodyum, paladyum, ve platin gibi platin grubu elementler (PGE) bakımından zengin oluşu ekonomik değerini artırmakta; kromit yataklarında yaygın olarak bulunan olivin ve serpantin gibi mineraller de sanayi açısından ayrı bir önem taşımaktadır. Ekonomik potansiyeline rağmen, krom cevheri atıklarının uygunsuz şekilde yönetilmesi su ve toprak kirliliği ile hava kirliliği gibi ciddi çevresel tehditler oluşturmaktadır. Bu sorunlar, PGE'ler dahil olmak üzere toksik ağır metallerin varlığıyla daha da ağırlaşmaktadır. Bu etkileri azaltmak amacıyla, kromit atıklarının ikincil hammadde olarak değerlendirilmesine yönelik ilgi giderek artmaktadır. Bu atıklardan değerli bileşenlerin geri kazanılması, çevresel riskleri azaltmakla kalmayıp kaynakların daha sürdürülebilir kullanımına da katkı sağlamaktadır. Bu çalışma, maden atıklarından krom geri kazanımına yönelik küresel ve yerel çabaları incelemekte ve Türkiye genelinde bu süreçlerin geliştirilip, yaygınlaştırılmasının önemini vurgulamaktadır. Bu tür uygulamaların teşvik edilmesi, hem çevrenin korunması hem de önemli ekonomik faydalar sağlanması açısından büyük önem taşımaktadır. Çalışmanın temel amacı, sürdürülebilir krom geri kazanımını destekleyerek ekolojik dengenin korunmasını ve kaynak verimliliğinin artırılmasını sağlamaktır.

Anahtar Kelimeler: Ağır metal, Krom cevheri, Krom geri kazanımı, Plâtin grubu elementler (PGE'ler), Maden atıkları yönetimi, Çevresel sürdürülebilirlik.

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1. Introduction

Chromite crystal, with the general chemical formula (Mg, Fe^{2+}) (Cr, Al, Fe^{3+})$_2O_4$, serves as the primary mineral constituent of chromite rock (Akmaz, 2018). Chromite ore serves as a critical raw material across various industries, with its primary applications being in the metallurgical (80-85%), chemical (8-10%), and refractory (7-9%) sectors. Notably, it demonstrates exceptional resistance to atmospheric conditions and does not corrode in humid environments. Although chromium occurs in various minerals such as kemererite and uvarovite, chromite remains the sole economically viable source for chrome ore production.

Chromite ore extracted in Türkiye is characterized by high chromium (Cr) content but relatively lower iron (Fe) content (Akın, 2018), making it particularly well-suited for metallurgical applications. Beyond its metallurgical utility, chromium plays a vital role in the automotive, aerospace, and machinery industries due to its exceptional durability and resistance to corrosion. Moreover, the economic significance of chromite ore is further elevated by its enrichment with PGEs. Since the latter half of the 20th century, PGEs have become indispensable in modern industry. Their widespread applications are driven by unique properties such as excellent electrical conductivity, resistance to high temperatures, and immunity to oxidation and chemical corrosion, earning them the designation of "miracle metals" in the literature (Garuti, 2009; Sahu et al., 2018). Additionally, the catalytic efficiency of certain PGEs in numerous chemical reactions further enhances their industrial value, solidifying their importance in contemporary technological advancements (Uysal, 2007).

The ophiolitic rocks of Upper Cretaceous age are widely distributed in Türkiye, resulting in the country's significant deposits of podiform chromitites associated with these rocks. Approximately 2,000 chromitite occurrences of varying sizes have been documented (Uysal, 2007; Akmaz, 2013), and chromium production is actively carried out. However, the by-products generated during the production process are of particular concern due to their environmental implications. These residues often contain heavy metals, chemical compounds, and other potentially toxic substances, posing substantial environmental risks. Improper extraction and processing of chromite ore can result in considerable amounts of solid and liquid waste, contributing to environmental pollution. Recent research on the recovery of chromium from chromite residues has demonstrated that efficient recovery is achievable through methods such as magnetic separation, multi-gravity separation and column flotation (Tripathy et al., 2019; Izerdem, 2024; Xu et al., 2025). Furthermore, the recovery of PGEs, which are essential by-products of chromite ore and critical for industrial applications, holds great significance. The importance of PGE recovery is heightened by the limited lifespan of global reserves, emphasizing the need for effective utilization of these resources. The improper management of residual materials generated during and after chromite ore production poses a significant environmental threat, particularly in Türkiye. Although there are existing efforts related to chromium waste recovery in Türkiye, they remain insufficient in addressing the growing scale of the issue. It is essential that such practices be extended to all regions where chromium production is actively carried out. This study evaluates both global and national approaches to the management of chromite residues and focuses on assessing their potential for use as secondary raw materials within the Turkish context. Moreover, it aims to highlight the need for expanding the number of such initiatives in order to minimize the environmental and health-related risks associated with chromium waste.

2. The Methods Used in Chromite Deposits

The grade values of chromite ore in Türkiye exhibit significant variation. Specifically, 83% of the ore has a Cr_2O_3 content below 10%, 12% falls within the range of 10-35%, and only 5% has a grade of 35% or higher (Akın, 2018). This distribution underscores the critical importance of chromite ore beneficiation processes in the country. As in many parts of the world, the shaking table technique is predominantly employed for chromite ore enrichment in Türkiye (Fig. 1). This method leverages differences in specific gravity, where crushed chromite ore is washed on a shaking table using water. The denser chromite ore is segregated to one side, while the lighter gangue material is carried to the other side by the combined effects of water flow and shaking. Through this process, the beneficiation of chromite ore is effectively achieved.

Figure 1. Representative examples of ore enrichment plants utilizing the shaking table.

Improper management of chromite ore extraction and subsequent beneficiation processes poses significant environmental risks. To address these hazards, one of the most effective approaches is the utilization of chromite residues as secondary raw materials. Recent studies have demonstrated that chromium recovery from these residues is feasible, particularly through the application of techniques such as magnetic separation, multi-gravity separation, and column flotation (Chowdhury et al., 2025; Fig. 2).

Figure 2. Key techniques employed in the chromium recovery process (URL-1, 2024).

Equally critical to the recovery of residues from chromite ore is the extraction of heavy metal elements, particularly PGEs, present in the ore. Catalytic converter waste is frequently utilized in this recovery process. Initially, the converter waste is shredded and ground, followed by the separation of metallic components through magnetic and stripping techniques. Subsequently, all materials are pulverized into fine powder, which is then placed in sample containers for analysis. Analytical techniques such as X-ray fluorescence (XRF) and X-ray diffraction (XRD) are commonly employed to evaluate the powdered material, completing the PGE recovery process (Fig. 3).

Figure 3. Analytical tools utilized in the recovery of PGEs.

3. Results and Discussion

3.1. Uses of Chromium and Platinum Group Elements

Chromium, one of the most significant elements in nature, is an essential component of modern industry. Although numerous chromium-containing minerals exist, chromite ore is the sole economically viable source for chromium production (Demir et al., 2023). The applications of chromium derived from chromite ore are concentrated in three primary industrial sectors: metallurgical, chemical and refractory industries. Approximately 85% of global chromite ore production is consumed by the metallurgical industry, while 8% is utilized in the chemical industry, and the remaining 7% is employed in the refractory industry (Uysal, 2007). The Cr_2O_3 content of chromite ore determines its industrial application: less than 40% Cr_2O_3 for refractories; 40-46% Cr_2O_3 for refractories, chemicals, and metallurgy; and over 46% Cr_2O_3 for metallurgy and chemicals.

Chromitites are predominantly found within upper mantle peridotites, such as harzburgite and dunite. Consequently, alongside chromite ore, they often contain industrially valuable minerals like olivine and serpentine. Olivine crystals are commonly used in industry as substitutes for limestone, dolomite, and silica sand. Forsteritic olivine, which is rich in Mg and Si, offers significant economic, health, and environmental advantages when used in blast furnaces in place of these materials. Its primary industrial applications are in the iron-steel, refractory, and foundry industries. In addition, olivine is utilized in agriculture, environmental technologies, and the treatment of industrial waste (Turan and Acartürk, 2022). Serpentine minerals, when aggregated, form the rock serpentinized peridotite, which is often used as a decorative stone similar to marble. Moreover, serpentine minerals are important materials in the construction, insulation, and thermal isolation sectors (Jain et al., in press).

In addition to its industrial utility, the presence of platinum group elements significantly enhances the economic value of chromite ore. These elements exhibit remarkable resistance to chemical reactions at high temperatures and exceptional catalytic properties, making them indispensable in industries such as chemical manufacturing, petroleum refining and automotive production. PGEs are also utilized as corrosion-resistant materials in the chemical, electrical (e.g., telecommunications and consumer electronics), glass, dental and medical industries. Furthermore, platinum, in particular, is highly sought after for use in jewelry (Akbulut, 2009; USGS, 2017). The role of PGEs in the development of hydrogen-fueled, environmentally friendly vehicles further underscores their importance. These vehicles rely on fuel cells, which generate electricity by combining hydrogen (fuel) and oxygen (from the air) in a channel coated with platinum. During this process, hydrogen and oxygen gases react, facilitated by the catalytic properties of platinum, to produce electricity with water as the only by product. This pollution-free technology positions PGEs as critical components in advancing sustainable automotive solutions for the future.

3.2. Chromite and PGE Deposits of Türkiye

The geological evolution of Türkiye is rooted in the lithospheric fragments of the continental margins of Gondwana and Laurasia, which converged during the Alpine Orogeny following the collision of the Arabian Plate with the Anatolian Plate in the Late Cretaceous-Tertiary period (Şengör and Yılmaz, 1981; Yılmaz, 1993; Bozkurt and Mittwede, 2001; Ustaömer et al., 2009). This tectonic amalgamation resulted in the extensive distribution of ophiolitic rocks across the region during the Upper Cretaceous (Fig. 4). Consequently, Türkiye hosts significant deposits of podiform chromitites associated with these ophiolitic complexes. To date, approximately 2,000 chromitite formations of varying sizes have been identified across the country, and chromite ore is extensively mined in these regions (Akbulut et al., 2010; Akmaz et al., 2014; Uysal et al., 2015, 2018; Avcı et al., 2017; Chen et al., 2019, 2021; Liu et al., 2023). The chromite deposits in Türkiye can be categorized into six principal regions, ranked by their significance: (1) Guleman (Elazığ), (2) Sivas-Erzincan-Kop Mountain, (3) Fethiye-Köyceğiz-Denizli, (4) Mersin-Adana-Kayseri, (5) Bursa-Kütahya-Eskişehir, and (6) İskenderun-Gaziantep (Fig. 4) (URL-2, 2022; Demir et al., 2023). These regions collectively underscore the country's substantial contribution to global chromite production.

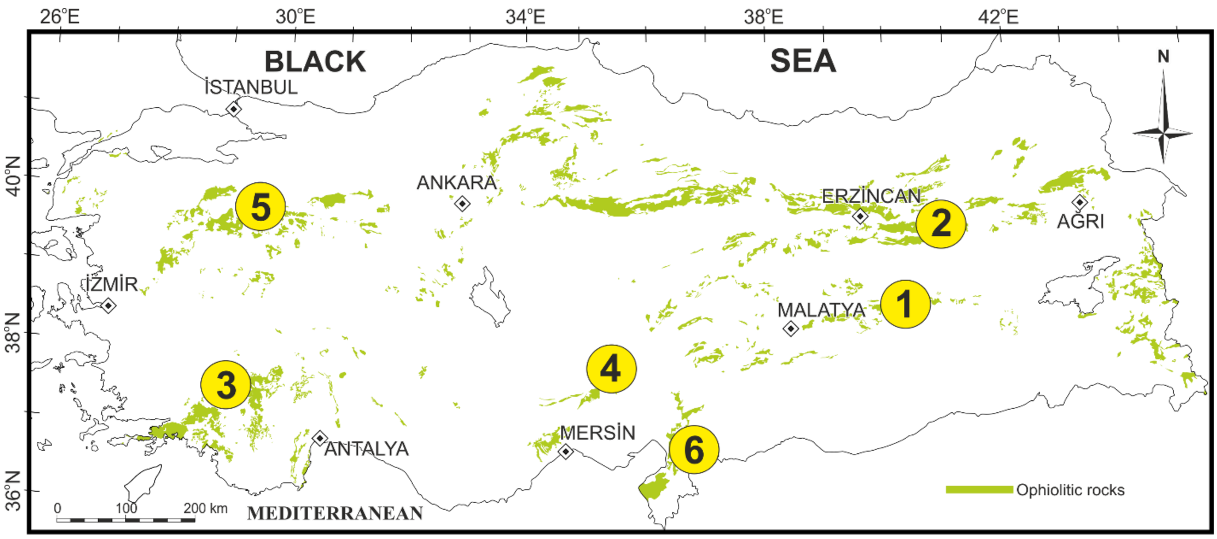

Figure 4. Spatial distribution of ophiolitic rocks in Türkiye and the primary regions hosting significant podiform chromitite deposits (adapted from Akmaz et al., 2014).

Turkish chromite deposits predominantly exhibit lenticular forms, characteristic of typical podiform chromitite deposits (Fig. 5a). In addition to this configuration, they may also occur as longitudinally developed veins (Fig. 5b). The chromite ore primarily displays massive and disseminated textures (Fig. 5c, d), although banded and nodular textures are occasionally observed (Fig. 5e, f). Podiform chromitites are generally discordant with the surrounding mantle peridotites. Within the mantle peridotites, primarily harzburgite and dunite, chromitites often exhibit sharp and, in some cases, graded contacts with the host rocks. These chromitites are frequently encased by dunitic envelopes of varying thickness (Akmaz, 2018).

Globally, the chemical composition of ophiolitic chromitites exhibits a wide range of variability, and these chromitites are generally classified into two main types: Al-rich and Cr-rich chromitites (Ahmed and Arai, 2002; Gervilla et al., 2005;

González-Jiménez et al., 2011). Similarly, ophiolitic chromitites in Türkiye are typically found in two compositional groups high-Cr and high-Al types (Uysal et al., 2007, 2009; Akmaz et al., 2014). However, in recent years, a new compositional type, referred to as intermediate chromitites, has also been identified within Turkish chromitite occurrences (Uysal et al., 2016, 2018; Chen et al., 2019; Liu et al., 2019).

The region is notably rich in upper mantle rocks, which are predominantly composed of olivine crystals. As a result, it hosts substantial olivine reserves (Turan and Acartürk, 2022). For instance, a study conducted in the northern part of the ultrabasic massif near Orhaneli identified distinct dunite zones and revealed an estimated reserve exceeding 5 billion tons in that area alone (DPT Raporu, 2001). When fresh olivine minerals undergo hydration, they alter into serpentine-type minerals. In olivine-dominated environments, serpentine crystals commonly coexist with olivine. Thus, the region is considered highly rich in both olivine and serpentine minerals.

The PGEs hosted within chromitites are predominantly concentrated in the Earth's upper mantle. The primary geological settings associated with PGE-bearing deposits include: layered intrusions (stratiform-type chromitites), ophiolites (podiform-type chromitites), Ural-Alaskan-type complexes (Ural-Alaskan-type chromitites) and sedimentary basins (black shales) (Uysal, 2007). At present, commercial PGE production is primarily derived from stratiform type chromitites within large mafic-ultramafic layered complexes (Akbulut, 2009). These Precambrian-aged chromitites (approximately 2 to 2.7 billion years old) exhibit ore body thicknesses ranging from a few millimeters up to 2 meters, and laterally, they may extend over several kilometers reaching up to 150 km in some cases (Schulte et al., 2010). The most significant PGE producing complexes worldwide include the Bushveld Complex (South Africa), the Great Dyke (Zimbabwe) and the Stillwater Complex (USA). In contrast, other types of chromitite deposits are generally considered unsuitable for PGE production due to geological constraints, high production costs, and technical challenges. The PGE content in podiform chromitites associated with ophiolitic rocks is generally below 500 ppb (Malitch et al., 2003; Zhou et al., 2014; Saveliev, 2024). Similarly, the PGE concentrations in Türkiye's chromitite deposits are relatively low, consistent with other ophiolitic chromitites worldwide. However, localized PGE enrichments have been documented in certain regions of Türkiye. For example, the total PGE content has been reported as 6.3 ppm in the Berit chromitites (Kahramanmaraş) (Kozlu et al., 2014), 4.15 ppm in the Elmaslar chromite deposit (Denizli) (Akbulut et al., 2010), and 2.8 ppm in chromitites from Southeastern Türkiye (Malatya) (Akmaz et al., 2014). Although Turkish ophiolitic chromitites may occasionally exhibit localized PGE enrichment, they are generally considered inadequate for economically viable PGE production. Given the steadily increasing global demand for PGEs and the significant depletion of existing reserves, the recycling of PGEs has become critically important both in Türkiye and worldwide. The recovery of PGEs directly from chromitites poses considerable technical and economic challenges, making such processes largely inefficient. Therefore, the extraction of PGEs from secondary sources particularly from PGE-bearing materials such as automotive catalytic converters represents a more practical and sustainable alternative.

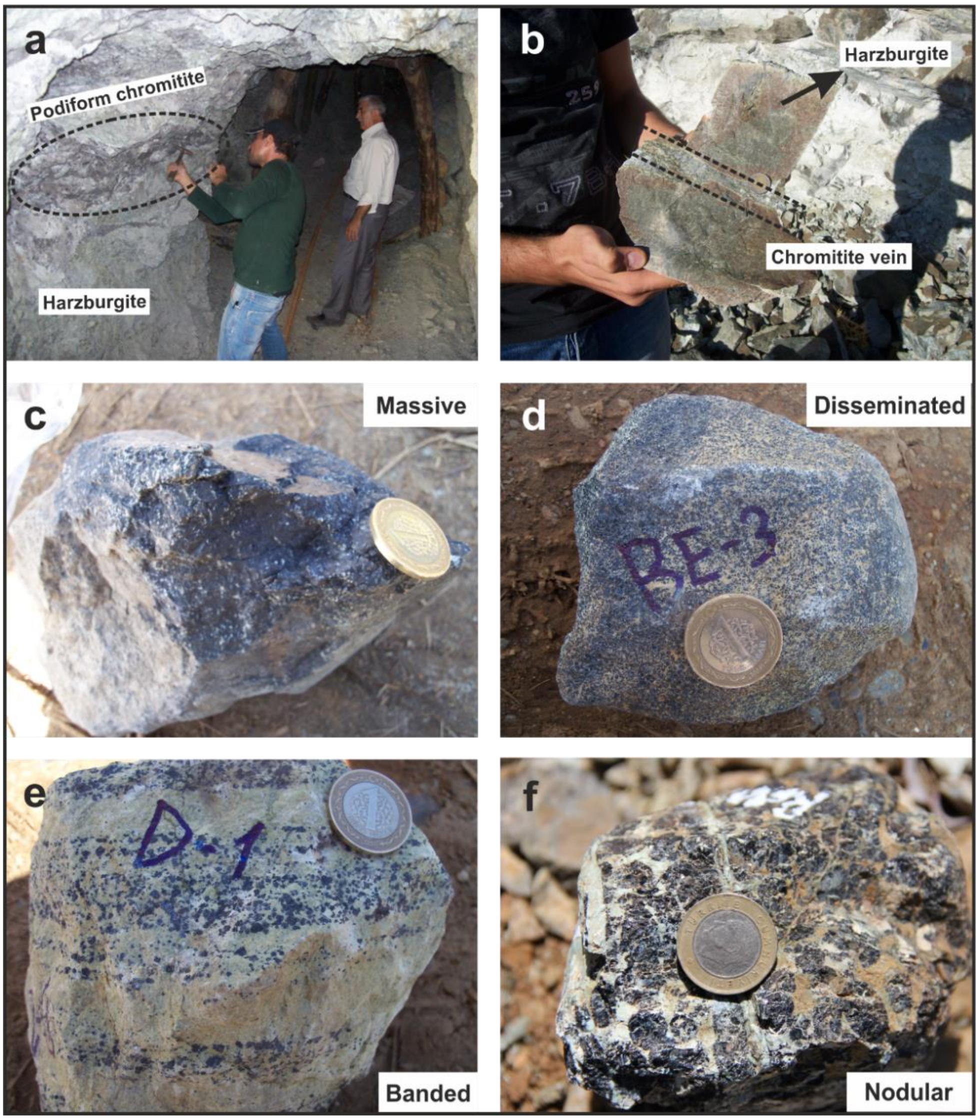

Figure 5. Field photographs of chromite ore occurrences in Türkiye. Lenticular chromite deposits (a) and vein-like chromite formations (b) within harzburgite. Textural variations in chromitite samples include massive (c), disseminated (d), banded (e), and nodular textures (f) (Akmaz, 2013).

3.3. Chromite Production in Türkiye

Türkiye boasts a rich history of chromite mining, with activities tracing back to 1850. The first discovery of chromium occurred in 1848 near Harmancık (Bursa, Türkiye) marking the beginning of an industry that would grow to become a cornerstone of Türkiye's economy. Chromium was established as a key export commodity in 1868 (Taşlıgil and Şahin, 2015) and by 2023, Türkiye emerged as the second-largest chromite-producing country globally, surpassed only by South Africa (URL-3, 2024). The country's chromite deposits are primarily of the podiform type, characterized by their lens-shaped formations and mining operations are adapted to the specific size, depth and topographic features of each deposit.

Historically, chromite mining in Türkiye relied heavily on open-pit methods, particularly for high-grade deposits located near the surface. Over time, the depletion of these easily accessible reserves has necessitated a shift toward underground mining methods, targeting both high-grade and lower-grade ores. This transition has been facilitated by advancements in mining technology and ore processing techniques, enabling the efficient exploitation of deeper and more complex deposits. Türkiye's legacy in chromium mining is evidenced by the coexistence of active licensed mines, modern beneficiation facilities, and numerous abandoned or inactive sites. These inactive sites, along with the residues from historical mining and ore processing activities, contain significant volumes of chromite waste. This chromite waste represents an untapped resource, offering considerable potential for secondary raw material production, particularly in light of increasing global demand for chromium and the growing emphasis on sustainable resource management. Moreover, Türkiye's strategic geographic location between Europe and Asia enhances its importance as a chromium supplier, ensuring efficient access to international markets. Investments in modern technologies, including advanced ore beneficiation techniques and environmentally sustainable waste recovery processes, position Türkiye as a critical player in global chromite production while addressing environmental concerns and contributing to the circular economy.

Globally, chromite reserves are estimated at approximately 3.6 billion tons, with the vast majority around 96% concentrated in South Africa, Zimbabwe, and Kazakhstan. Among these, South Africa holds the largest share, accounting for nearly 84% of the world's total chromite reserves. Although Türkiye's chromite reserves represent only about 0.2% of global reserves, the country remains a significant player in terms of the quality of ore produced rather than the quantity of its reserves (Demir et al., 2023). The total known run-of-mine (ROM) chromite ore resource in Türkiye is estimated at approximately 242,341,000 tons. Notably, 83% of this resource originates from low-grade deposits containing less than 10% Cr_2O_3. Only about 5% of the total resource (approximately 13,087,000 tons) consists of high-grade ore ($\geq$ 35% Cr_2O_3) that can be sold directly without further processing (Akın, 2018). In Türkiye, annual chromite production fluctuates in response to a variety of factors, including macroeconomic conditions, international demand, ore price volatility, and trade dynamics (URL-4, 2025). Over the ten-year period from 2012 to 2021, the highest level of run-of-mine chromite production was recorded in 2012 at 12.43 million tons, while the lowest was in 2016 with 6.06 million tons. Production data show a consistent decline from 2012 through 2017, with the 2016 output representing an approximate 51% decrease compared to 2012 levels (Fig. 6; URL-5, 2025). This trend underscores the sensitivity of Türkiye's chromite industry to both domestic and global economic variables.

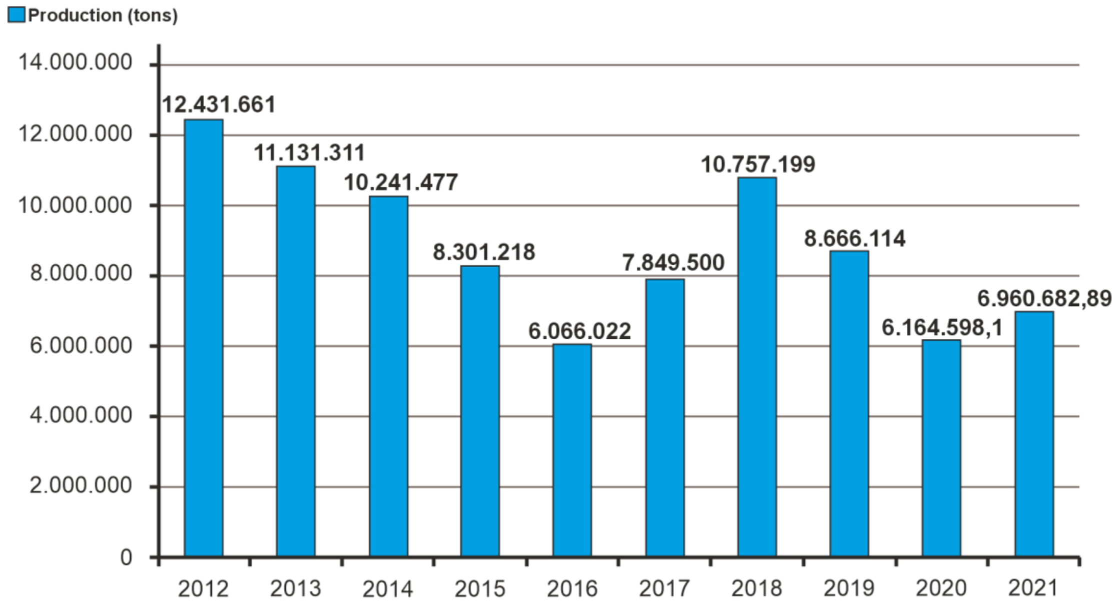

Figure 6. The run-of-mine chromium production in Türkiye (2012-2021 years) (modified from URL-5, 2025).

In addition to chromite, minerals such as olivine and serpentine are also produced in Türkiye. Rich olivine deposits are found in Muğla, and olivine mining is especially carried out in Köyceğiz (Muğla, Türkiye). Also, olivine mining is carried out in Bursa-Orhaneli. These deposits are processed through size reduction and classification before being marketed. Although not as extensively as olivine, serpentine minerals present in the ore are also produced (Turan, 2022). The ten-year (2020–2011) olivine ore production values in Türkiye are presented in Table 1 (Turan and Acartürk, 2022). Accordingly, the highest olivine production was recorded in 2019, with 469,545 tons. The second highest production occurred in 2018, with 411,612 tons. On the other hand, the lowest olivine ore production in Türkiye was in 2013, with 126,990 tons (Table 1).

Table 1. Olivine mine production values in Türkiye

Olivine	Production (tons)
2020	269,553.76
2019	469,545
2018	411,612
2017	177,493
2016	304,279
2015	184,623
2014	244,138
2013	126,990
2012	244,753
2011	221,079

3.4. Recovery of Chromite Ore and Platinum Group Elements

The extraction of chromite ore and subsequent enrichment processes must be conducted with the utmost precision to mitigate environmental risks. Chromium residues often contain heavy metals, chemical compounds and other potentially toxic substances, which, if improperly managed, can lead to significant environmental pollution. Inadequate extraction and processing methods result in the generation of substantial quantities of solid and liquid waste, contributing to severe environmental hazards such as water contamination, soil degradation, and air pollution. Addressing these risks requires a comprehensive approach that emphasizes the utilization of chromium residues as secondary raw materials. The development and implementation of advanced industrial residue treatment technologies play a crucial role in this effort. By enabling the conversion of residues into commercially valuable products, these technologies not only mitigate environmental damage but also promote sustainable resource utilization (Tastanov et al., 2023). A notable example is the Kef mining region in Elazığ, Türkiye, operated by Eti Krom I.C., which has accumulated approximately 1 million tons of ore residue earmarked for further processing. These residues are processed using gravitational and magnetic separation methods to recover valuable minerals such as serpentine, olivine and chromite (Fig. 7). The company’s long term goal, within the framework of a seven year project, is to recycle the entire volume of residues in the Kef tailings dam with zero environmental harm. This initiative is expected to generate both economic and environmental value while reducing waste generation through modern mining practices. Another example of chromium residue recovery is observed at the Üçköprü enrichment plant in Fethiye (Muğla, Türkiye) where chromium residues are processed to remove environmental contaminants and recover valuable chromium content (Yüce et al., 2005). The recovery process involves magnetic separation and column flotation techniques. Research indicates that this process can yield a concentrate with a minimum Cr_2O_3 grade of 46% and an average recovery efficiency of 60%. Additionally, the sandy material larger than 0.1 mm, separated through washing and sieving, has been identified as suitable for use as lightweight building material, further enhancing the utility of the residues.

Another example involves a study on chromium recovery from waste material remaining after the beneficiation of chromite ore in the Mersin region (Türkiye; Mirdalı, 2007). In this research, the chemical composition of the chromite ore waste was first analyzed (Table 2). Subsequently, a particle size distribution was obtained by subjecting the waste material to sieve analysis. Finally, based on the results of scanning electron microscopy (SEM), water absorption, and mechanical strength tests, it was demonstrated that chromite waste could be effectively utilized as a modifying additive in the production of ceramic floor tiles and porcelain tiles.

Table 2. Chemical analysis of chromite rust (wt%)

Oxide	Chromite Rust (%)
SiO_2	30,85
Al_2O_3	1,05
TiO_2	0,02
Fe_2O_3	7,11
CaO	0,51
MgO	40,50
Na_2O	0,01
K_2O	0,01
Cr_2O_3	4,30
MnO	0,09
NiO	0,30
A.Z	15,18

Beyond Türkiye, similar advancements have been demonstrated in the treatment of chromite ore residues from the Kempirsayi podiform chromites in Kazakhstan. These residues, characterized by exceptionally high Cr_2O_3 content (95.61%), were processed through chemical and gravitational enrichment methods. The resulting chromium concentrate achieved a Cr_2O_3 grade of 49.48%, illustrating the potential for high-value recovery from residues (Tastanov et al., 2023).

These examples underscore the importance of integrating modern residue treatment technologies into mining operations to enhance resource recovery, reduce environmental impact, and contribute to sustainable industrial practices. By transforming mining waste into valuable products, such initiatives not only address environmental concerns but also support economic development and resource efficiency.

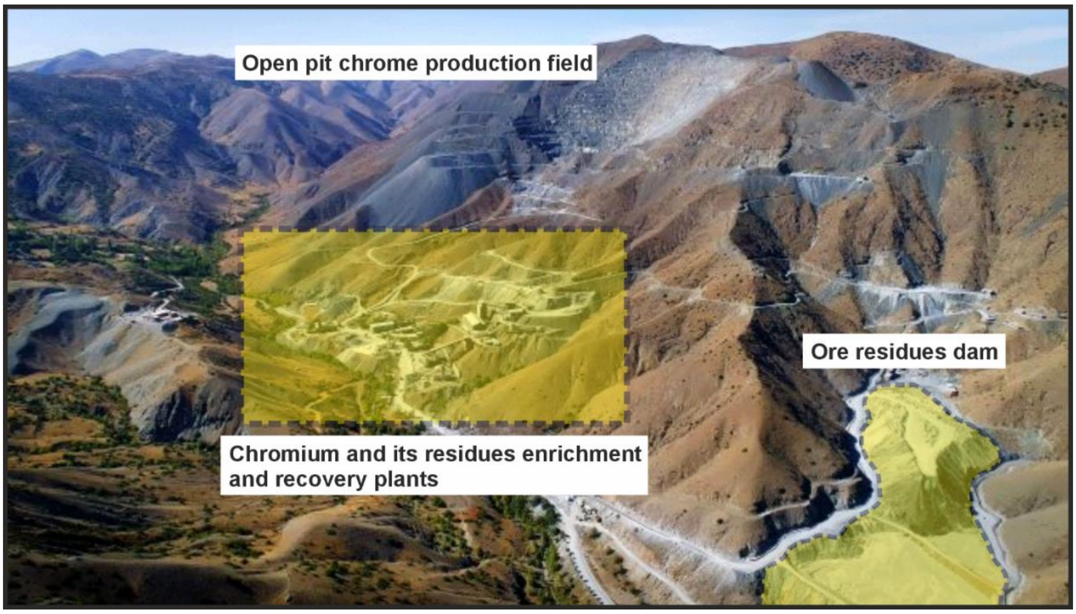

Figure 7. Chromium recovery pilot plant operated by Eti Krom I.C. in Elazığ.

The recovery of PGEs has gained significant importance in recent years due to their high production costs, increasing global demand and the ongoing depletion of natural reserves (Ngcephe, 2019). PGEs are primarily utilized as autocatalysts, making their recycling a critical focus, particularly from discarded catalytic converters. In a recent study, catalytic converter waste was first shredded and ground to facilitate processing (Ngcephe, 2019). The ground material was then completely dissolved using the sodium peroxide fusion method. Advanced analytical techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FT-IR), LECO microelement analysis and nuclear magnetic resonance (NMR), were employed to isolate and characterize the dissolved material. This process ultimately resulted in the successful recovery of a substantial amount of PGEs, highlighting the efficacy of such recycling methods.

3.5. Utilization of Turkish Chromite Ore Residues as Secondary Raw Materials

Chromium is a critically strategic element, both for current industrial applications and future technological advancements, with chromite mineral serving as its sole viable source. Türkiye is endowed with significant chromite ore deposits, particularly concentrated in regions such as Elazığ and its surroundings. In addition to chromite ore deposits, Türkiye also has a significant number of deposits containing industrially useful minerals such as olivine and serpentine. Especially in the waste materials obtained as a result of chromite beneficiation processes, minerals like olivine and serpentine are found alongside chromite ore. Around many chromite mining sites in Türkiye, there are large amounts of waste rock (pasa) left behind in abandoned conditions. These materials are rich in the aforementioned minerals. From the waste materials generated during chromite beneficiation and the discarded materials around abandoned mining sites, not only can chromite be recovered, but minerals such as olivine and serpentine can also be extracted. In this way, Türkiye could gain much greater economic benefit from chromite recovery processes than initially expected. Chromite ore production is conducted extensively across the country; however, in certain cases, mining residues are disposed of in an irregular and unplanned manner, resulting in environmental hazards (Fig. 8). These improperly managed residues pose significant risks to soil, water and air quality, necessitating the implementation of systematic control and management measures. Recycling chromite ore residues presents an effective solution to these environmental challenges, with proven applications both internationally and within Türkiye. To address this issue, a centralized and strategically located storage area near major chromite production sites can be established to facilitate the organized containment of these residues. Recovery facilities can then be constructed in proximity to these storage locations, enabling the efficient recycling of residual materials. Such recovery processes would not only mitigate the environmental impact of mining residues but also provide substantial economic benefits by transforming waste into valuable secondary raw materials.

This approach aligns with sustainable development principles, contributing to a cleaner and more livable environment while enhancing the economic output of Türkiye's chromite mining sector. By integrating environmentally conscious waste management practices into the mining industry, Türkiye can establish a model for balancing industrial activity with ecological preservation and resource efficiency.

Figure 8. An inactive chromite quarry and its associated residues in the Amanos Mountains, Hatay.

4. Conclusions

Türkiye is among the leading chromite ore producers globally, contributing significantly to its economy through substantial annual revenues generated from chromium exports. Chromium and platinum group elements are of strategic importance for the nation's industrial and technological future, given their critical applications in metallurgy, chemical industries, automotive production, aerospace and advanced catalytic systems. In addition, minerals such as olivine and serpentine, which have various industrial applications and are associated with chromite deposits, are also found in large quantities in Türkiye. The recovery of such industrial ores is of great importance.

However, the improper management of residual materials generated during chromite extraction and processing poses significant environmental risks, including soil degradation, water contamination, and air pollution. These challenges emphasize the urgent need for sustainable management and recovery strategies to mitigate the environmental impact and optimize resource utilization.

The recovery and utilization of chromite ore residues as secondary raw materials represent a practical and sustainable solution to these challenges. As demonstrated by successful examples globally and in Türkiye, these residues can be processed to recover valuable chromium, olivine, serpentine and PGEs through advanced techniques such as magnetic separation, multi-gravity separation, column flotation, and chemical treatments. Moreover, recycling processes not only reduce environmental hazards but also contribute to economic gains by transforming mining waste into commercially valuable products.

The next critical step is to scale up and expand existing recovery practices across the country. Establishing centralized storage facilities near major chromite production sites and developing dedicated recovery plants in these locations can streamline residue management and recycling efforts. By adopting such an integrated approach, Türkiye can balance its industrial growth with environmental stewardship, setting a model for sustainable mining practices.

The broader implementation of residue recovery technologies will provide dual benefits: enhancing Türkiye's economic output by maximizing resource efficiency and improving environmental quality to create a more sustainable and livable environment. With concerted efforts to increase the number of chromium recovery facilities nationwide, Türkiye has the potential to secure its position as a global leader in chromite production while addressing pressing environmental concerns. Such advancements will ensure the country not only capitalizes on its rich chromite reserves but also demonstrates a commitment to responsible and forward-looking industrial practices.

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All the authors declare no conflict of interest.

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No Ethics Committee Approval is required for this study.

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