

Review

Treatment of Refractory Oxidized Nickel Ores (ONOs) from the Shevchenkovskoye Ore Deposit

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Abstract

The increasing depletion of high-grade nickel sulfide deposits and the growing demand for nickel have intensified global interest in oxidized nickel ores (ONOs), particularly those located in Kazakhstan. This study presents a comprehensive review of the mineralogical and chemical characteristics of ONOs from the Shevchenkovskoye cobalt–nickel ore deposit and other Kazakhstan deposits, highlighting the challenges they pose for conventional beneficiation and metallurgical processing. Current industrial practices are analyzed, including pyrometallurgical, hydrometallurgical, and pyro-hydrometallurgical methods, with an emphasis on their efficiency, environmental impact, and economic feasibility. Special attention is given to the potential of hydro-catalytic leaching as a flexible, energy-efficient alternative for treating low-grade ONOs under atmospheric conditions. The results underscore the necessity of developing cost-effective and sustainable technologies tailored to the unique composition of Kazakhstani ONOs, particularly those rich in iron and magnesium. This work provides a strategic framework for future research and the industrial application of advanced leaching techniques to unlock the full potential of Kazakhstan’s nickel resources.

Keywords: oxidized nickel ores; Shevchenkovskoye ore deposit; leaching technologies; nickel extraction; laterite processing



Academic Editor: Petros E. Tsakiridis

Received: 30 June 2025

Revised: 28 July 2025

Accepted: 29 July 2025

Published: 6 August 2025

Citation: Tauakelov, C.A.; Rakhimbayev, B.S.; Yskak, A.; Valiev, K.K.; Tastanov, Y.A.; Ibrayev, M.K.; Bulaev, A.G.; Daribayeva, S.A.; Kazbekova, K.A.; Joldassov, A.A. Treatment of Refractory Oxidized Nickel Ores (ONOs) from the Shevchenkovskoye Ore Deposit. *Metals* **2025**, *15*, 876. <https://doi.org/10.3390/met15080876>

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1. Introduction

Nickel is a silver-white, refractory metal with a melting point of 1453 °C [1]. It is hard, ductile, malleable, highly stretchable, and polishes well. Chemically, it is relatively inert [2]. The Clarke value of nickel in the Earth’s crust is 0.0058%. Its concentration in ultrabasic rocks ($1.2 \times 10^{-1}\%$) is approximately 200 times higher than in acidic rocks ($8 \times 10^{-4}\%$) [3,4]. Five stable isotopes of nickel are known: ^{58}Ni , ^{60}Ni , ^{61}Ni , ^{62}Ni , and ^{64}Ni , among which ^{58}Ni is the most abundant [5].

Nickel is extensively used in metallurgy [6], accounting for approximately 80% of total consumption, primarily for the production of alloy steels and various alloys [7,8]. Major consumers of nickel alloys include the automotive industry, machine tool manufacturing, and the electronics sector. Nickel forms widely utilized alloys with copper, zinc, and aluminum (e.g., brass, nickel silver, cupronickel, and bronze), as well as with chromium (nichrome). Other important nickel-containing materials include coinage alloys (75% Cu + 25% Ni) and platinite (49% Ni + 51% Fe) [9]. In the chemical and food industries, pure nickel is employed in the fabrication of various equipment, including crucibles, pipes, instruments, and vessels for the evaporation of essential oils. Nickel-based alloys find applications in jet aviation, rocket engineering, and the manufacture of equipment for the nuclear industry [10,11]. In the 20th century, nickel steels were widely utilized for the production of armor, gun barrels, crankshafts, and other critical components [12].

Oxidized nickel ores from Kazakhstan deposits exhibit significant variability in their mineralogical composition, both in terms of valuable constituents and gangue minerals. At present, effective beneficiation methods for such ores are lacking, leading to the processing of ores with low nickel grades, typically ranging from 0.7% to 1.5%. An additional challenge is their high hygroscopicity: the content of constitutional moisture can reach 10–15%. In international practice, such ores are predominantly processed using hydrometallurgical methods. The leaching temperature range varies from 80 to 270 °C, depending on the applied technology. The most extensively utilized techniques include high-pressure acid leaching (HPAL) at elevated temperatures of 240–270 °C and atmospheric acid leaching within the range of 80–100 °C. Alternative approaches, such as the direct nickel process and chloride-based leaching methods, operate under moderate thermal conditions (80–150 °C); however, their commercial implementation remains limited to date. At the same time, in CIS countries, pyrometallurgy remains the primary method for the direct processing of oxidized nickel ores [13–15].

The Shevchenkovskoye cobalt–nickel ore deposit is located in the Kostanay Region of Kazakhstan and forms part of the Western Turgay Nickel District. This district comprises a cluster of nickel deposits situated in the western section of the Turgay depression, including the Shevchenkovskoye, Kundybay, Podolskoye, Zhitikarinskoye, Akkarginskoye, Milyutinskoye, and other deposits [16–18].

The deposit hosts reserve of nickel (1.075 million tonnes) and cobalt (585.9 thousand tonnes), with the total value of the mineral resources exceeding 5.6 trillion tenge (national currency of Kazakhstan) [19–21].

According to the data from the national company Kazakh Invest, the Shevchenkovskoye deposit contains 104.4 million tonnes of cobalt–nickel ore with an average nickel grade of 0.79% (corresponding to 657.4 thousand tonnes of metal in category C1 and 266.6 thousand tonnes in category C2) and an average cobalt grade of 0.045% (34 thousand tonnes of metal in category C1 and 16.7 thousand tonnes in category C2) [13].

The main objective of this study is to provide a comprehensive review and critical analysis of existing processing technologies for refractory oxidized nickel ores (ONOs) in the context of the Shevchenkovskoye deposit in Kazakhstan. Particular emphasis is placed on evaluating the feasibility, efficiency, and environmental sustainability of hydro-catalytic as a prospective alternative to conventional methods.

This work is significant for several reasons. First, Kazakhstan possesses substantial reserves of oxidized nickel ores that remain underutilized due to the lack of economically viable processing technologies. Second, existing pyrometallurgical methods are not well suited for low-grade ONOs with high iron and magnesium content, typical of Kazakh deposits. Third, the current global trend towards cleaner and more energy-efficient met-

allurgical processes necessitates the development of new solutions tailored to regional ore characteristics.

By analyzing mineralogical features, identifying processing challenges, and comparing global technologies, this study provides a strategic foundation for selecting and optimizing future technologies and approaches. The findings are intended to support national efforts to unlock Kazakhstan's nickel potential through sustainable, cost-effective metallurgical innovation.

The construction of the manuscript is as follows:

Section 2: Raw Material Base, including

- Classification and characteristics of nickel ore types.
- Global reserves and resource distribution.
- Major nickel-bearing countries and deposits.

Section 3: Characteristics of Oxidized Nickel Ores (ONOs):

- Genesis and distribution.
- Industrial types and chemical composition.
- Mineralogical features and processing challenges.

Section 4: Kazakhstani Deposits of Oxidized Nickel Ores:

- History and status of ONO mining in Kazakhstan.
- Key deposits and exploration regions.

Section 5: Processing Methods for Oxidized Nickel Ores (ONOs)

- Pyrometallurgical methods.
- Shaft and electric furnace smelting.
- Ferronickel and matte production.
- Ausmelt process.
- Hydrometallurgical methods.
- HPAL (high-pressure acid leaching).
- Heap and underground leaching.
- Pyro-hydrometallurgical methods.
- Caron process.
- Combined flowsheets and ammonia leaching.

Section 6 reviews processing technologies, evaluates their efficiency, and highlights the potential of hydro-catalytic leaching.

Section 7 summarizes the manuscript.

2. Materials and Methods

Raw Material Base

The physicochemical properties and processing methods of ore materials largely depend on their chemical and mineralogical composition. A brief overview of the raw material base of the nickel sector in the non-ferrous metallurgy industry is presented below.

Nickel ores occur in nature in three main forms:

1. Supergene (silicate) deposits.
2. Sulfide copper–nickel deposits.
3. Deep-sea iron–manganese nodules formed on the ocean floor.

Despite the high potential of iron–manganese nodules as a source of nickel, their extraction is associated with significant technical and economic challenges [22–25]. Therefore, currently, the primary sources of nickel are two types of deposits:

- Supergene silicate ores, where the main nickel-bearing minerals are nickeliferous limonite and garnierite;
- Magmatic sulfide copper–nickel ores, where pyrrhotite (iron–nickel sulfide) is predominant.

The global resource base comprises over 400 nickel ore deposits, of which approximately 240 are of the sulfide type and more than 150 are of the silicate type. However, only a limited number of these deposits are suitable for economically viable industrial mining and processing. Depending on the volume of proven reserves, deposits are classified as follows:

- Unique—more than 1 million tonnes of nickel.
- Very large—from 500 thousand to 1 million tonnes.
- Large—from 250 thousand to 500 thousand tonnes.
- Medium—from 100 thousand to 250 thousand tonnes.
- Small—less than 100 thousand tonnes.

The unique deposits in terms of reserves include the sulfide deposits of Norilsk-1, Talnakh, and Oktyabrskoye (Russia); Sudbury and Thompson (Canada); Agnew, Kambalda, and Mount Keith (Australia); Jinchuan (China); Maksut (Kazakhstan); as well as oxidized deposits on the island of Euboea (Greece), in Nepoui (New Caledonia), Pomalaa and Gebe (Indonesia), and Moa Bay (Cuba), with initial reserves exceeding 1 million tonnes of nickel [26,27].

The main reserves of sulfide nickel ores are concentrated in Russia and Canada. These ores are of complex composition, containing not only nickel but also copper, cobalt, platinum, platinum-group metals (palladium, iridium, ruthenium, osmium), as well as gold and silver. The primary ore minerals include nickeliferous pyrrhotite (Fe_7S_8), pentlandite ($(\text{Ni},\text{Fe})_9\text{S}_8$), and chalcopyrite (CuFeS_2). In addition, ores commonly contain, in smaller amounts: magnetite (Fe_3O_4), ilmenite (FeTiO_3), pyrite (FeS_2), cubanite (CuFe_2S_3), millerite (NiS), heazlewoodite (Ni_3S_2), polydymite (Ni_3S_4), violarite (Ni_2FeS_4), bravoite ($(\text{Fe},\text{Ni},\text{Co})\text{S}_2$), siegenite ($(\text{Co},\text{Ni})_3\text{S}_4$), cobalt–nickel pyrite ($(\text{Co},\text{Ni},\text{Fe})\text{S}_2$), among others. The content of the main components typically varies within the following ranges: nickel—0.4–2.0%, copper—0.2–2.0%, iron—10–30%, and sulfur—5–20%.

In addition to Russia and Canada, sulfide deposits are also found in South Africa, Australia, Zimbabwe, and Finland. However, in Russia, they play a leading role in nickel supply, whereas abroad their significance is secondary [26,28].

From a processing perspective, sulfide ores are significantly more convenient and economically advantageous compared to oxidized ores. Due to the presence of various valuable associated components, they enable a high coefficient of comprehensive raw material utilization. The primary processing method for such ores is flotation, and currently, sulfide ores remain the main source of industrial nickel production.

Nevertheless, in recent years, there has been a depletion of explored sulfide deposits with high metal grades. At the same time, the explored reserves of oxidized nickel ores remain substantial, making them a promising target for further development.

As of today, nickel resources have been identified in 38 countries worldwide. The total proven reserves are estimated at approximately 160 million tonnes. About 55% of the world's confirmed reserves are concentrated in five countries: Russia, Cuba, New Caledonia, Australia, and Indonesia.

From a geological and industrial classification standpoint, approximately 70% of global nickel resources are represented by lateritic (oxidized) ores—around 197.4 million tonnes—whereas sulfide ores account for about 30%, approximately 83.8 million tonnes.

According to data from the World Bureau of Metal Statistics (WBMS) [20], in 2024, the visible demand in the global nickel market was lower than supply by 136.7 thousand tonnes. According to WBMS, refined nickel production for the year amounted to 3.556 million tonnes, while consumption reached 3.4194 million tonnes.

More detailed information on the distribution of global nickel resources is presented in Table 1.

Table 1. Major proven nickel reserves.

Country	Identified Thousand Tons	Resources		Average	
		Share in the World, %	Reliable Thousands of Tons	Share in the World, %	Content of Ni, %
Russia	27.900	9.8	22,100	13.7	1.32
Finland	4300	1.5	2350	1.5	0.3
Indonesia	30.500	10.7	17,000	10.5	1.76
Kazakhstan	1900	0.7	1900	1.2	1.5
China	10.100	3.5	6750	4.2	1
Philippines	13,660	4.8	8330	5.2	1.42
Madagascar	1480	0.5	1395	0.9	1.04
South Africa	18.650	6.5	10,020	6.2	0.17
Brazil	18.050	6.3	9960	6.2	1.15
Guatemala	4600	1.6	2735	1.7	1.63
Canada	12.190	4.3	8200	5.1	1.07
Cuba	20.120	7.1	13,400	8.3	1.3
USA	6100	2.1	1900	1.2	0.85
Australia	49.400	17.3	26,400	16.4	0.78
New Caledonia	20.000	7	7200	4.5	1.93
Others	45.975	16.3	21,704	13.2	
Total	284.925	100	161,344	100	

3. Characteristics of Oxidized Nickel Ores (ONOs)

Oxidized nickel ores form as a result of prolonged exposure to natural factors acting on the parent rocks under near-surface conditions. These types of ores are predominantly found in regions with a tropical climate and high weathering intensity, especially near the equator, as well as in arid zones. Major countries where they are distributed include Australia, South Africa, New Caledonia, Cuba, the Philippines, Indonesia, and others [26,29,30].

Oxidized ores, containing oxide and silicate forms of nickel, have long been a major source for extracting this metal. Their industrial development began in the late 1880s with the exploitation of deposits in New Caledonia.

Currently, oxidized nickel ores are classified into four main types, each characterized by its own mineralogical composition. Approximate values for the composition of these industrial types are provided in Table 2.

Table 2. Classification and Composition of Industrial Types of Oxidized Nickel Ores.

Type of Ore	Content, %				Metal Content Ratio		Characteristic Deposits
	MgO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	Fe–Ni	Ni–Co	
Magnesian (Serpentinic)	18	43	17	5	2:1	27:1	Kimpersai (Kazakhstan), New Caledonian (Australia), Cuban (Cuba)
Alumino-Magnesian	13.0	41.0	18.0	12.0	8:1	50:1	Ufaley (Russia)
Ferruginous-magnesian (nontrotitic)	8.0	41.0	25.0	6.0	17:1	20:1	Kimpersai (70%) (Kazakhstan), Pobuzhskoye (Russia)
Ferruginous-siliceous (transitional)	4.0	32.0	44.0	7.0	33:1	13:1	Buruktal, Shevchenkivske (Kazakhstan), Yelizavetinskoye
Ferruginous (ochreous-chamositic)	7.0	18.0	46.0	7.0	40:1	8:1	Serovskoye (Russia)
Ferruginous (ochreous, lateritic)	2.5	10.0	63.0	5.0	50:1	8:1	Kimpersai (Overburden) (Kazakhstan)

Oxidized nickel ores used in industrial processing, by both foreign and domestic enterprises, in most cases contain between 1.2% and 1.5% nickel. However, in recent years, there has been a trend towards the processing of lower-grade ores with reduced nickel content, due to the depletion of high-grade resources and the need to expand the raw material base [31–35].

The typical chemical composition of oxidized nickel ores processed at foreign enterprises is presented in Table 3.

Table 3. Chemical composition of oxidized nickel ores (dry basis).

Deposits	Ni	Co	Fe	Cr	Components, %		Mg	SiO ₂	CaO
					Mn	Al			
Goro-1	1.51	0.072	49.7	2.55	0.51	3.08	0.66	3.7	0.08
Goro-2 (New Caledonia)	1.65	0.12	6.1	0.52	0.25	0.44	20.2	43.7	0.17
Mindanao (Philippines)	2.8	0.1	17.1	0.8	-	0.16	13.1	28.1	low
Surigao (Philippines)	0.75	-	47.8	2.8	-	4.4	-	1.08	-
Manicani (Philippines)	0.5–1	-	50.2	2.7	-	3.2	-	2.6	-
Rarona (Indonesia)	0.37	-	50.2	2.1	-	3.7	-	0.63	-
Morro do Engenho (Brazil)	1.37	0.1	26.7	-	-	3.2	5.8	30	0.15
Moa, Cuba	1.4	0.14	47.5	2.5	0.8	4.5	1	2.5	0.02

The mineral composition of oxidized nickel ores is highly complex. In these ores, nickel is present in the form of silicates, oxides, and hydroxides, incorporated into various minerals. This type of material is characterized by fine-grained and amorphous-crystalline nickel distribution, which significantly complicates its extraction. In addition to the primary metal, the ores typically contain minor amounts of cobalt and copper—generally less than 1% relative to the nickel content.

The physicochemical properties of oxidized ores include a porous and friable structure, low mechanical strength, high hygroscopicity (up to 40%), and low bulk density (ranging from 1.1 to 1.3 t/m³) [36–39].

Due to the fine dispersion of nickel predominantly in the form of oxides, these ores are not amenable to effective beneficiation by conventional physicochemical methods, necessitating the use of alternative technological approaches. As a result, the ore with a nickel content of approximately 1% is directly processed metallurgically, requiring large-scale production to ensure economic efficiency.

Depending on the composition of the ore-forming minerals and associated components (such as nickel, cobalt, iron, magnesium, silica, and alumina), oxidized nickel ores are classified into two main types:

- Iron-rich ores (including ochreous, lepto-chloritic, and hematitic varieties);
- Magnesium-rich ores (predominantly serpentinites enriched with nickel-bearing silicates).

Deposits of oxidized ores are formed under supergene conditions, that is, within the near-surface weathering zone of the Earth's crust. Lateritic (iron-rich) ores, characterized by high iron content (over 35%) and low nickel and magnesium content, are found in the upper layers. In the lower sections, magnesium-nickel rocks—mainly serpentinites and garnierites—are found, with a high magnesium oxide content (up to 35–40% MgO) and elevated nickel content but reduced iron content (less than 20%).

From a mineralogical perspective,

- Limonitic ores consist mainly of iron oxides and hydroxides;
- Serpentine ores consist of iron–magnesium silicates.

Thus, the chemical composition of oxidized nickel ores can vary significantly, and the mineralogical composition primarily differs in the proportion of basic minerals, despite the ores' similar origin.

Nickel in both ore types usually substitutes isomorphically for iron or magnesium in the crystal lattice of oxides or silicates. It is present in the form of complex hydrated nickel-

magnesium silicates of variable composition, commonly referred to as garnierite, numeite, and others. A generalized chemical formula for these minerals is $(\text{Ni,Mg})\text{SiO}_3 \cdot n\text{H}_2\text{O}$.

It is important to note that cobalt distribution within the deposits does not correlate with nickel distribution; areas with elevated cobalt content and low nickel content, and vice versa, are common. Iron content in the ores is also independent of the nickel content.

Among the gangue components in oxidized nickel ores, aluminosilicates—clay minerals with the formula $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ —are frequently encountered and contribute significantly to the ore's high hygroscopicity. Quartz (SiO_2) and talc ($3\text{MgO} \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$) are also commonly present, with talc significantly raising the melting temperature of the material and complicating the metallurgical processing.

Undesirable impurities negatively affecting the processing and the final product quality include elements such as copper, chromium, and phosphorus. The characteristics of the main nickel-bearing minerals found in oxidized ores are presented in Table 4.

Table 4. Major nickel oxide minerals.

Name	Chemical Formula	Ni, %
Garnierite	$(\text{Ni, Mg})_4[\text{Si}_4\text{O}_{10}] (\text{OH})_4 \cdot 4\text{H}_2\text{O}$	16–35
Revdinskite	$(\text{Ni, Mg})_8[\text{Si}_4\text{O}_{10}] (\text{OH})_8$	16–35
Nickel-bearing kerolite	$(\text{Mg, Ni})_4[\text{Si}_4\text{O}_{10}] (\text{OH})_4 \cdot 4\text{H}_2\text{O}$	10–15
Nontronite	$m\{\text{Mg}_3[\text{Si}_4\text{O}_{10}](\text{OH})_2\} \cdot p\{(\text{Al,Fe})_2 \cdot [\text{Si}_4\text{O}_{10}] (\text{OH})_2\}$	0.5–2.0
Nickel-bearing serpophite	$(\text{Mg, Ni, Fe})_6[\text{Si}_4\text{O}_{10}] (\text{OH})_8$	4–5
Nickel-bearing hydrochlorite	$(\text{Mg, Al, Fe})_6 [(\text{Si, Al})_4\text{O}_{10}] \cdot (\text{OH})_8 \cdot n\text{H}_2\text{O}$	2–6
Asbolane, psilomelane varieties	$m(\text{Co, Ni})\text{O} \cdot \text{MnO}_2 \cdot n\text{H}_2\text{O}$	0.8–2.0

4. Kazakhstani Deposits of Oxidized Nickel Ores

Over the past 80 years, approximately 40 silicate-type nickel and cobalt deposits have been discovered in Kazakhstan, associated with ochreous-nontronitic weathering crusts of ultramafic rocks. All of them are located within the Kempirsai ultrabasic massif in the Mugodzhaz Mountains (Western Kazakhstan) and historically formed a major mineral resource base for the Orsk and Buruktal nickel plants, built nearby in the Orenburg region (Russia). Today, most of these deposits have been depleted. By the end of the 20th century, about 3 million tonnes of ore, or around 30 thousand tonnes of nickel, were mined annually from these deposits. Mining operations ceased in the early 2000s, and currently, approximately 250 thousand tonnes of nickel remain in the subsurface. Exploration for cobalt–nickel silicate-type deposits has also been conducted in other regions of Kazakhstan, leading to the discovery of several promising ore prospects in Northern and Eastern Kazakhstan. Notable among them are the Shevchenkowskoye (Figure 1) and Kundybayskoye deposits on the western flank of the Torgai Trough and the Gornostayevskoye deposit near the Irtysh River. Currently, 10 nickel-bearing districts have been identified in Kazakhstan, featuring extensive development of nickel-bearing weathering crusts of ultramafic rocks, and one district in Eastern Kazakhstan showing certain prospects for the discovery of sulfide copper–nickel deposits. Among the former, which are prospective for silicate ores, five main nickel-bearing districts stand out: western Kazakhstan, southern Mugodzhaz, western Torgai, eastern Kazakhstan, and central Kazakhstan. In Eastern Kazakhstan, small-scale exploration for sulfide copper–nickel deposits has also been conducted, resulting in the discovery of the small Yuzhny Maksut deposit and several promising ore occurrences within the Zharmasaur structural–formational zone.



Figure 1. Shevchenkovoyskoye cobalt–nickel ore deposit (Kostanay region of Kazakhstan).

The Sevchenkovskoye ore deposit is located in the Zhitikara District of the Kostanay Region, Republic of Kazakhstan, approximately 22 km southwest of the city of Zhitikara. This deposit is a typical example of a silicate-type nickel ore deposit. The primary valuable components are nickel and cobalt, while exploratory drilling has also been conducted to investigate the presence of rare earth elements including yttrium, cerium, neodymium, samarium, europium, gadolinium, praseodymium, lanthanum, and erbium, the spatial extent of the Shevchenkovskoye deposit covers an area of 291.8 km².

The largest nickel ore deposits are concentrated in the Aktobe Region, specifically within the Batamshinskaya group of deposits, which includes Nickel'tau, Rozhdestvenskoye, Kokpektinskoye, among others, with explored economic reserves reaching up to 423.5 million tonnes. In Eastern Kazakhstan, significant deposits include Belogorskoye, Karaul-Tobe, Kyzyltyrskoye, Bukorskoye, and Gornostayevskoye. A distinctive feature of oxidized nickel ores is the variability in their chemical and mineralogical composition.

On average, the ores contain 1.4% nickel, though certain areas exhibit concentrations ranging from 1.5% to 3.0%. Typically, the deposits are composed of chains of ore bodies separated by barren rock zones. The size of individual ore bodies varies considerably: the smallest range from 220 to 360 m in length and from 50 to 140 m in width, while the largest extend from 1500 to 2000 m in length and from 320 to 700 m in width. Extraction is conducted via cost-effective open-pit mining methods; however, this approach involves the removal of significant volumes of waste rock.

5. Processing Methods for Oxidized Nickel Ores (ONOs)

Based on the analysis of the chemical and material composition of various types of nickel ores, several key conclusions can be drawn that determine approaches to their industrial processing.

The coefficient of comprehensive raw material utilization (CRMU), which reflects the degree of involvement of all valuable components in processing, varies significantly depending on the ore type. For complex sulfide ores, such as those processed at the facilities of MMC Norilsk Nickel, the CRMU can exceed 50%, indicating high efficiency in extracting not only nickel but also accompanying components (copper, cobalt, platinum-group metals, etc.). In the case of oxidized nickel ores (ONOs), this indicator is significantly lower and generally does not exceed 15%, due to the mineralogical form of nickel and its fine-grained distribution in the ore mass.

Reducing fuel and energy resource (FER) consumption during ore processing is possible through the application of autogenous smelting processes, particularly in the treatment of sulfide feedstock enriched with sulfur. In such cases, the sulfur contained in the ore partially replaces the need for external fuel, resulting in the high energy efficiency of the processes.

Regarding ONOs, their processing, especially via reductive-sulfurizing shaft smelting to produce matte, presents certain challenges. The key issues include high coke consumption, which is a costly component of the metallurgical process; and the generation of low-grade sulfur-containing gases, requiring additional costs for gas treatment and disposal, thereby increasing both environmental and economic burdens on production.

Depending on the physical and chemical characteristics of the ores, processing may be carried out using different technological approaches. Currently, three main groups of technologies for the extraction of metals from ONOs have been developed and are being applied:

Pyrometallurgical processes—based on the high-temperature treatment of ores. They provide rapid response times and large-scale production capabilities but require significant fuel expenditures and create challenges in waste management.

Combined pyro-hydrometallurgical technologies—integrating stages of both high-temperature and liquid-phase processing. This approach partially compensates for the drawbacks of each method and improves the overall metal recovery efficiency.

Hydrometallurgical processes—characterized by milder processing conditions, the ability to extract metals from low-grade ores and sludges, and higher environmental sustainability. They are particularly effective for the treatment of iron-rich (lateritic) ores.

Currently, hydrometallurgical and combined processes together account for about 61% of all nickel produced from oxidized ores, while pyrometallurgical methods account for approximately 39%. This highlights the growing interest in flexible and environmentally sustainable processing methods.

It should also be noted that the choice of processing technology largely depends on the mineralogical composition of the ore:

For magnesian-type ores (with high MgO content), pyrometallurgical methods are most suitable, being employed in approximately 75% of cases.

For iron-rich (lateritic) ores, which predominantly contain iron oxides, hydrometallurgical processes such as acid and ammonia leaching are more effective.

Typical flowsheets for the processing of ONOs are presented in Figure 2.

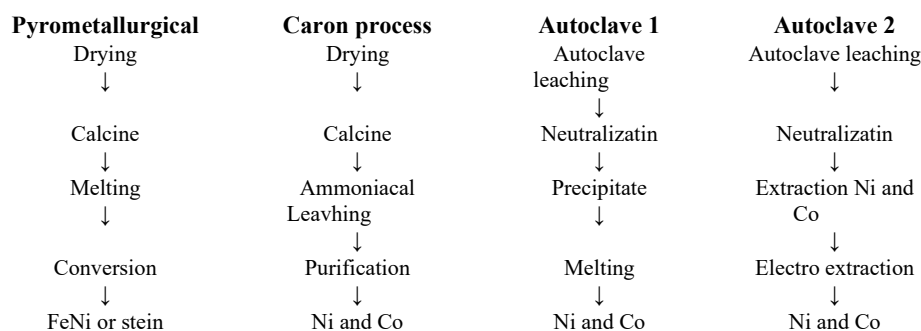


Figure 2. Process flow diagrams for laterite ore processing. Adapted from Ref. [40].

Currently, the most widely used method for processing oxidized nickel ores (ONOs) abroad is smelting to produce ferronickel. High-temperature pressure acid leaching (HPAL) and the Caron process are employed to a lesser extent. Among pyrometallurgical processes, smelting to produce nickel pig iron (NPI), which is used in stainless steel production, is gaining increasing popularity [40].

5.1. Pyrometallurgical Methods for Processing Oxidized Nickel Ores

Pyrometallurgical methods for processing oxidized nickel ores (ONOs) include two main approaches: shaft furnace smelting to produce matte, followed by converting to finematte, achieving nickel recovery rates of 70–80%, or reductive electric furnace smelting to produce ferronickel (or nickel pig iron) with subsequent refining, allowing the recovery of up to 90% of nickel and 85% of cobalt into the final product. Both methods are effective for relatively high-grade ores, such as those suitable for producing high-quality ferronickel, with nickel contents exceeding 2.2% and Fe–Ni ratios of 5 to 6:1. For low-grade ferronickel production, ores containing at least 1.5% nickel and a high Fe–Ni ratio (ranging from 6 to 12:1) can be utilized. Matte smelting requires a combined nickel and cobalt content of at least 1.5%, as well as specific proportions of iron and silica. Internationally, ferronickel smelting is primarily applied to the processing of high-grade garnierite ores with nickel contents exceeding 1.2%. However, this technology demands high energy consumption and does not allow for the separate recovery of cobalt. Cobalt incorporated into ferronickel is priced as nickel, despite cobalt's significantly higher market value. Iron-rich oxidized nickel ores are not used for ferronickel production, mainly due to their elevated chromium content (1–4%).

A promising development direction for the pyrometallurgical processing of oxidized nickel ores is the application of the Ausmelt process. This technology can be used for the production of various non-ferrous metals, as well as ferroalloys, iron, and steel.

The Ausmelt technological scheme for processing oxidized nickel ores involves two furnaces: a smelting furnace and a reduction furnace. In this process, oxidized ore, after preliminary drying, is fed into the smelting furnace along with fluxes, secondary materials, and reductants (coke, coal). Fuel- and oxygen-enriched air are injected into the smelting bath via the Ausmelt lance. All process parameters are carefully controlled, and the nickel alloy is periodically tapped from the furnace. For slag depletion, a second Ausmelt furnace is used, where slag flows through a transfer system. In this furnace, coarse coal is introduced to reduce the remaining nickel into an iron-rich alloy. The resulting alloy is periodically tapped for recycling back to the smelting furnace, while the processed slag is continuously removed via an overflow siphon, granulated, and sent to waste disposal (Table 5).

Table 5. Major international producers processing oxidized nickel ores using pyrometallurgical methods.

Producer	Start-Up Year	Ni Content in Initial Ore, %	Product	Ni Content in Product, %	Production Capacity, Thousand t/Year
Doniambo, New Caledonia	1958	2.7	Fineststein	25	49
P.T. Inco, Indonesia	1977	1.97	Fe-Ni	78	11
Pacific Metals, Japan	1966	2.4	Fineststein	79	43
Falconbridge, Dominican Republic	1971	1.75	Fe-Ni	14–22	48
Cerro Matoso, Colombia	1982	2.9	Fe-Ni	38	30
Larco, Greece	1966	1.25	Fe-Ni	45	27
Hyuga Smelter, Japan	1956	2.4	Fe-Ni	24–30	19.5
Anglo American, Venezuela	2000	2.1	Fe-Ni	20–25	22
P.T. Aneka Tambang, Indonesia	1975	2.25	Fe-Ni	20	17
				25	11

Further laboratory studies and pilot-scale trials are required before this technology can be implemented in full-scale industrial production [41].

Numerous studies focused on the analysis of pyrometallurgical processes for the treatment of laterite ores [33,42–49] confirm that, despite the widespread use of pyrometallurgical methods for processing oxidized nickel ores (ONO), they have several significant drawbacks.

The processes are highly energy-intensive—roasting and melting of the ore to form slag at temperatures around 1600 °C require substantial fuel and electricity consumption. Melting costs account for approximately half of the material expenses, and the processing of low-grade ores significantly reduces the economic efficiency of pyrometallurgical methods.

Nickel and cobalt losses increase considerably with higher slag production and increased iron oxide content in the slag.

The low nickel content in oxidized nickel ores (ONOs) (less than 1%), rising energy prices, and increased ore transportation tariffs hinder technological and equipment improvements from achieving sufficient economic efficiency in the pyrometallurgical processing of oxidized nickel ores.

5.2. Hydrometallurgical Methods for Processing Oxidized Nickel Ores (ONOs)

Modern hydrometallurgical processing schemes for ONOs are based on the direct leaching of nickel and cobalt using sulfuric acid, without prior ore roasting. This process can be implemented in two main variants. In the first case, raw material treatment is carried out under autoclave conditions (autoclave sulfuric acid technology); in the second, heap or underground leaching methods (geotechnological methods) are employed, which are currently under development and preparation for industrial application [50].

Heap leaching, widely used for copper and gold extraction, is characterized by low capital and operating costs [51–53]. Therefore, the application of this technology for nickel extraction appears promising. The principles of organizing heap leaching for ONO are similar to those used for copper and gold leaching. Sulfuric acid solutions with a concentration of 50–100 g/L are used for leaching, enabling the extraction of nickel as well as iron and magnesium. However, this process results in the formation of silica gel. The main challenge of heap and underground leaching, especially for low-grade ores with a nickel content below 1%, is that sulfuric acid leaching produces complex solutions with low nickel concentrations (approximately 1 g/L) and high concentrations of impurity metals: iron up to 10 g/L, magnesium up to 15 g/L, along with significant levels of silicon, aluminum, chromium, manganese, and others. The primary methods for processing such solutions are solvent extraction and sorption. The efficiency of nickel and cobalt extraction and the production of purified metals determine the success of geotechnological methods.

An additional problem with heap and underground leaching methods is that oxidized nickel ores often contain significant amounts of clay minerals and fine particles, which hinder solution percolation through the ore layers [54].

Other disadvantages of geotechnological methods include high sulfuric acid consumption for magnesian ores, low nickel recovery rates, difficulties in separating leach solutions from residues, long leaching durations, and insufficient nickel recovery due to the inability to acid-leach metals encapsulated in silicates. Furthermore, the formation of gelatinous silica complicates the process when using mineral acids. Nevertheless, these methods remain promising, especially for small oxidized nickel ore deposits [55–59].

The most widely used hydrometallurgical method for nickel production is high-pressure acid leaching (HPAL). Since the moisture content of ONOs ranges from 20 to 50%, drying costs accounted for up to 50% of the total energy consumption in the Caron process. Therefore, the direct autoclave leaching scheme proved to be more economically viable. Another advantage of the autoclave technology is the selective extraction of nickel and cobalt, whose sulfates remain stable at high temperatures ($>250\text{ }^{\circ}\text{C}$) and pressures. In contrast, ferric sulfate hydrolyzes under these conditions, precipitating as hydroxide. The industrial application of the HPAL process was first developed and implemented for low-magnesium ores (0.7–1.5% MgO) from the unique Moa deposit in Cuba in 1959. The ore pulp (with a solids content of up to 45%) was heated with live steam and then leached in vertical autoclaves. The process temperature was 240–250 $^{\circ}\text{C}$, the pressure 3.6–3.7 MPa, the design sulfuric acid consumption was 225 kg per ton of ore (actual consumption—240 kg/t), and the leaching duration was 1–2 h. Nickel and cobalt recoveries into the solution were about 95%. One major complication of the process was the deposition of aluminum and iron hydrolysis products (known as “scale”) on the internal surfaces of the reactors. The most widely applied hydrometallurgical method for nickel extraction is high-pressure acid leaching (HPAL). Given that the moisture content of oxidized nickel ores (ONOs) typically ranges from 20% to 50%, drying casts can account for up to 50% of the total energy consumption in the Caron process. Consequently, the direct autoclave leaching scheme has been proven to be more economically advantageous. An additional benefit of autoclave technology is the selective extraction of nickel and cobalt, whose sulfates remain stable under high-temperature ($>250\text{ }^{\circ}\text{C}$) and high-pressure conditions. In contrast, iron undergoes hydrolysis under these conditions, forming insoluble hydroxide, which enables its effective separation from the target metals during the leaching stage. Thus, the selective precipitation of iron at 240–250 $^{\circ}\text{C}$ within the autoclave can be regarded as a key technological advantage of the HPAL process, significantly reducing the load on subsequent solution purification stages. Scale formation accounted for 28–33% of the ore mass, with less than 0.1% depositing on the equipment and over 99.9% remaining attached to ore particles, thus slowing down the leaching process. Subsequently, nickel–cobalt sulfide precipitation is performed in horizontal cylindrical autoclaves, where pulp agitation is carried out by gaseous hydrogen sulfide at 120–135 $^{\circ}\text{C}$ and 1.0 MPa pressure. Part of the recycled sulfide precipitate is used as a seed material at a 2:1 ratio to the newly formed precipitate. The resulting sulfide precipitate captures 99% of the nickel and 98% of the cobalt. The sulfide nickel–cobalt concentrate contains approximately 55% Ni and 5% Co.

The nickel–cobalt concentrate is further processed at the Fort Saskatchewan plant (Canada) using an improved ammonia–sulfate autoclave leaching technology to produce nickel and cobalt powders. However, the energy savings achieved compared to the Caron process are partially offset by increased material costs for equipment resistant to the aggressive conditions of high-temperature acid leaching, as autoclaves are very expensive. Nevertheless, the development of autoclave technology was promoted by the implementation of

the “solvent extraction–electrowinning” (SX-EW) process, allowing for the production of cathode nickel, and the use of larger-volume autoclaves.

A drawback of autoclave sulfuric acid leaching is primarily its effectiveness for limonitic (low-magnesium) laterites with low contents of magnesium and aluminum oxides. This is because magnesium and aluminum are the main acid-consuming components in ONOs: 4.2 tons of sulfuric acid are required per ton of magnesium, and 5.5 tons per ton of aluminum. Therefore, if the MgO content exceeds 1.5%, acid consumption significantly increases, and it is not possible to reduce the magnesium dissolution without sacrificing nickel and cobalt recovery. Nonetheless, theoretically, autoclave sulfuric acid leaching can be applied to any oxidized nickel ores [60].

Another significant drawback of this technology is the difficulty of acid neutralization, leading to the formation of gypsum or magnesium-containing effluents. Attempts were made to avoid the use of autoclaves and neutralize some of the acid using saprolitic (high-magnesium) laterites, but even then, a considerable amount of magnesium sulfate remained, requiring disposal [61,62]. Currently, several nickel projects utilizing similar technologies have been implemented, such as the Ambatovy project in Madagascar [63], the Goro Nickel project in New Caledonia [64], and others under consideration (Table 6) [65–68].

Table 6. Plants operating with HPAL technology.

Company	Designed Capacity, T Ni/Year	Content in Ore, % Ni Co		Final Product
Moa Bay, Cuba	25,000	1.4	0.13	NiS-CoS
Murrin Murrin, Australia	40,000	0.99–1.3	0.07	NiS-CoS
Coral Bay, Philippines	20,000	1.26	0.12	NiS-CoS
Goro, New Caledonia	60,000	2	0.1	NiO
Ambatovy, Madagascar	60,000	1.1	0.1	Ni refined

As an alternative, less energy-intensive and more environmentally sustainable methods are being explored, including the direct nickel process (DNi process). This technology enables the efficient extraction of nickel and cobalt from laterite ores under atmospheric pressure and moderate temperatures (80–100 °C), utilizing recyclable reagents—typically nitric or citric acid in a complexing form. One of the key advantages of the DNi process is the near-complete recovery of reagents and the minimal generation of toxic waste, making it more environmentally friendly compared to conventional acid-based leaching methods [69]. The industrial implementation of this technology began in the 2020s, with projects launched in Australia (e.g., a plant in New South Wales) and planned facilities in Indonesia [70,71].

5.3. Pyro-Hydrometallurgical Methods for Processing ONOs

According to various studies, the majority of nickel in iron-rich laterite ores is present within goethite (α -FeOOH), while cobalt is almost always associated with manganese oxides [67]. Thus, the recovery of nickel and cobalt primarily involves their separation from iron and manganese.

Modern pyro-hydrometallurgical flowsheets for ONO processing include two main stages: the reductive roasting of the initial ore to prepare it for leaching (the pyrometallurgical stage) and leaching of the calcine followed by the treatment of multicomponent solutions using advanced hydrometallurgical methods, such as precipitation, sorption, solvent extraction, electrolysis, and others, which enable the production of purified commercial-grade non-ferrous metals [34,72].

The Caron process, one of the first combined technologies for ONO processing, was implemented at the Nicaro plant in Cuba, and later at the Yabulu plant in Australia, the Sao Miguel Paulista plant in Brazil (currently suspended), and at the Punta Gorda plant in

Cuba. The application of the Caron process is economically justified when processing ores with a magnesium content of up to 8%.

The Caron process is typically used for the treatment of limonite ores or blends of limonite and saprolite ores; however, an increase in saprolite content significantly reduces the recovery rates of nickel and cobalt. This process involves the thermal treatment of the initial ore under reducing conditions to achieve the selective reduction of nickel and cobalt, followed by leaching of the calcine using ammoniacal-carbonate solutions with the addition of oxygen. As a result, non-ferrous metals are transferred into the solution, while most of the iron precipitates in an insoluble form. This is due to the ability of ammoniacal solutions to form stable and highly soluble complexes with nickel and cobalt, such as $\text{Ni}(\text{NH}_3)_5\text{CO}_3$ and $\text{Co}(\text{NH}_3)_5\text{CO}_3$. An important aspect of the process is that it enables the almost complete regeneration of the primary reagent—ammonia—as well as the partial regeneration of carbon dioxide [73,74].

The Caron process allows for high recovery rates of nickel (up to 95%) and cobalt (70–72%), but results in relatively dilute solutions with nickel concentrations of 1.5–2.0 g/dm³ and cobalt concentrations of about 0.2 g/dm³.

However, this process has several significant drawbacks:

Ammoniacal leaching is not a universal method suitable for all types of oxidized nickel ores. For example, serpentine ores containing nontronite are poorly amenable to leaching due to their low reducibility. Nontronitic ores and unweathered serpentinites are virtually unreduced even at temperatures of 1000–1100 °C—and this type of ore predominates at most oxidized nickel deposits within the CIS countries.

Pyrometallurgical stages such as ore drying and reductive roasting are highly energy-intensive, accounting for more than 60% of the total energy consumption, while hydrometallurgical stages require various chemical reagents.

The filtration efficiency during this process is low due to the gelatinous structure of the precipitated iron hydroxide.

Low-metal recovery is observed in both the pyrometallurgical stage (due to forsterite formation) and the hydrometallurgical stage (due to the co-precipitation of cobalt and the blockage of leached particles by precipitated iron).

Overall nickel recovery reaches approximately 75%, while cobalt recovery is about 50%.

Thus, the overall efficiency of the “roasting–leaching” technology largely depends on the cost of fuel, which continues to rise. Accordingly, as indicated by techno-economic evaluations, the Caron process is inferior to direct ore leaching hydrometallurgical flow-sheets in key indicators such as production cost and nickel and cobalt recovery rates into commercial products (Table 7, adapted from refs. [75–78]).

Table 7. Plants using the caron process.

Company	Designed Capacity, T Ni/Year	Content in Ore, %		Final Product
		Ni	Co	
Nicar, Cuba	22.000	1.4	0.1	NiO sinter
Queensland Nickel, Australia	18.000	1.35	0.11	NiO granules, NiS-CoS
Nonoc, Philippines	30.000	1.22	0.1	NiO powder, NiS-CoS
Tocantins, Brazil	5000	1.6	0.14	Ni cathode

6. Discussion

At present, it is generally accepted that autoclave-sulfuric acid technology is characterized by lower specific capital investments and operating costs compared to ore smelting and reductive roasting followed by leaching, making it the comparatively most economically efficient method for processing oxidized nickel ores (ONOs) [73,74].

The use of nitric acid for ONO leaching is less common, and studies in this area are scarce in the literature. This can be attributed to the high volatility of nitrogen oxides and the complexity of solvent regeneration. Russian researchers [79] proposed a method for the nitric acid leaching of ONO at temperatures between 70 and 160 °C. The resulting slurry underwent hydrolysis to precipitate iron (as Fe_2O_3) and aluminum (as Al_2O_3), after which the precipitate was separated from the solution. Magnesium hydroxide ($\text{Mg}(\text{OH})_2$) was then added to the solution to precipitate nickel and cobalt as hydroxides. Nitrogen oxides were converted back into nitric acid (at temperatures of 125–200 °C) and returned to the process.

The authors [80] studied the process of the autoclave leaching of nickel and cobalt using nitric acid. In this process, iron remained in the form of an insoluble precipitate, which was proposed to be used as iron-containing feedstock. Nickel and cobalt were extracted sequentially from the neutralized leach solutions using sorption techniques, with nitrogen oxides being captured during the process.

There is also a method of leaching using a mixture of sulfuric and nitric acids [80]. In this process, nitric acid leaching was performed in autoclaves at pH 0.3–0.7, temperatures of 200–250 °C, and pressures of 4–6 MPa. Under these conditions, iron was oxidized and precipitated, while nickel and cobalt remained in the solution. The extraction rates of nickel and cobalt into solution were about 80%.

All these methods are characterized by significant emissions of nitrogen gases and the difficulty of acid regeneration. Currently, there are no data available on the industrial implementation of nitric acid leaching of ONOs, nor on the pilot-scale testing of such technologies.

Hydrochloric acid is a strong solvent that enables high extraction levels of valuable components from ore under atmospheric pressure. However, one of the main obstacles to the industrial-scale application of hydrochloric acid is its aggressive impact on processing equipment.

Experiments using hydrochloric acid for leaching oxidized nickel ores were carried out by G.G. Urazov [81]. Studies were conducted on ores from Ural deposits, where acetic acid was initially used, followed by the roasting of the leach residue and subsequent treatment with hydrochloric acid. The obtained solutions were purified from impurities, and nickel was precipitated in various compound forms. Nevertheless, this technology was never implemented at an industrial scale.

Currently, there are no operating facilities using the chloride leaching of oxidized ores, although research has been ongoing since the 1970s. Several potential process schemes have been proposed for practical implementation, and companies such as BHP Billiton, Jaguar Nickel, Nichromet Solutions Inc., Intec Ltd., and Anglo American (Anglo Research Nickel—ARNi process) continue to develop chloride-based technologies [82–85].

Despite various proposals in recent decades for implementing chloride leaching of oxidized nickel ores, none of these initiatives have progressed beyond even the pilot scale. The primary obstacles remain both environmental and technological in nature, including the high toxicity and regeneration, as well as the requirement for expensive corrosion-resistant materials. Moreover, the absence of the large-scale demonstration facilities significantly reduced the investment appeal of such technologies, especially in comparison to the well-established sulfuric acid leaching methods [86–89]. However, interest in this technology persists due to its advantages, such as there being

- No need for elevated pressures;
- Improved filterability of precipitates;
- The potential to produce valuable by-products.

The disadvantages of chloride technology include the requirement for more expensive materials for equipment and the necessity for acid recycling. Unlike sulfate technologies, the development of chloride schemes has received less attention, complicating direct comparisons between the two methods.

Intec Ltd. attempted to combine chloride and sulfate technologies. However, the iron and magnesium precipitates produced during chloride solution purification could not be utilized as commercial products, unlike calcium sulfate. Additionally, sulfuric acid consumption was high, and further research results were not published [61].

BHP Minerals developed a chloride-based heap leaching process, wherein nickel and cobalt are extracted from chloride solutions using ion exchange or precipitation with magnesium oxide. Iron was precipitated either with magnesium oxide or through pyrohydrolysis after liquid–liquid extraction. However, the former required significant amounts of magnesium oxide, and the latter entailed excessive energy costs for pyrohydrolysis, making these methods economically unfeasible.

The project closest to industrial realization is being developed by Jaguar Nickel Inc. for a facility in Guatemala, where it is planned to process laterite ore to obtain nickel and cobalt via hydrochloric acid leaching.

7. Conclusions

A review of the literature allows the following conclusions to be drawn. The relevance of research into the development of new technologies for processing oxidized nickel ores in Kazakhstan is driven by several important factors. Firstly, in recent years, the global market has seen a decline in nickel prices, while existing technologies do not meet energy-saving and environmental safety requirements, rendering them economically unviable. Meanwhile, Kazakhstan holds significant reserves of oxidized nickel ores, both in large and smaller deposits. These deposits are developed via open-pit mining, and the ores possess a relatively loose structure, reducing extraction costs.

Secondly, conventional physical beneficiation methods have proven effective, leading to the large-scale processing of primary ores through metallurgical routes. However, the application of pyrometallurgical technologies is economically unfeasible for low-grade silicate nickel ores due to their typically low nickel content (generally less than 1.5%) [90]. The processing of such ores requires extremely high temperatures (up to 1600 °C) and involves substantial costs related to energy consumption, specialized equipment, and fluxing additives [87]. Additionally, pyrometallurgical operations often result in the loss of valuable by-products (such as cobalt), the generation of large volumes of slag, and significant CO₂ emissions, all of which complicate environmental management and increase waste disposal costs [86].

In contrast, hydrometallurgical methods—such as high-pressure acid leaching (HPAL), atmospheric leaching (AL), and the direct nickel process (DNi)—offer higher recovery rates for nickel and cobalt, along with lower energy consumption and reduced environmental impact [69,91]. These advantages make them more suitable for processing low-grade silicate and laterite nickel ores under current industrial and environmental conditions.

Furthermore, the application of heap and in-situ leaching technologies is limited by both the chemical and mineralogical composition of the ores and their physical properties, which prevent the formation of heaps with good permeability characteristics.

Thus, the search for an optimal technology for processing Kazakhstan's oxidized nickel ores—one that enables the production of high-purity nickel, the efficient processing of ores with high iron and magnesium contents, and maximized nickel recovery into marketable products—is an extremely urgent task.

We have initiated exploratory research into hydro-catalytic agitated leaching using standard equipment. The application of a hydro-catalytic solution based on mineral acids in this process will allow for operation without pressure increase, the generation of well-filterable precipitates, and the processing of ores with a wide range of compositions.

Future trends in the extraction of nickel from oxidized nickel ores are focused on enhancing the process efficiency and environmental safety. Key areas of development include the advancement of hydrometallurgical technologies with improved reagent regeneration and reduced energy consumption, the integration of biotechnological approaches, the development of hybrid processing methods, and the implementation of selective metal recovery techniques aimed at minimizing waste generation. In parallel, increasing emphasis is being placed on the digitalization and automation of production processes, which will enable the optimization of operational parameters and a reduction in environmental impact. Collectively, these directions pave the foundations for the sustainable and economically viable nickel extraction from oxidized ores in the coming decades.

Author Contributions: Conceptualization, A.Y. and M.K.I.; methodology, B.S.R.; software, K.A.K. and A.G.B.; validation, Y.A.T. and K.K.V.; formal analysis, A.G.B. and A.A.J.; investigation, B.S.R. and C.A.T.; resources, A.Y.; data curation, S.A.D. and C.A.T.; writing—original draft preparation, S.A.D. and K.A.K.; writing—review and editing, B.S.R., Y.A.T. and K.K.V.; visualization, Y.A.T., M.K.I. and A.A.J.; supervision, A.Y., K.K.V. and Y.A.T.; project administration, A.Y.; funding acquisition, A.Y. All authors have read and agreed to the published version of the manuscript.

Funding: The research was performed in the framework of a grant program for scientific and/or scientific and technical projects, following a competition for grant funding for 2024–2026. The project is titled BR24992785 “Conducting research on the development of the agro-industrial complex of the Kostanay region with the establishment of a research center” and is funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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