metals

MDPI

Review

Options for Hydrometallurgical Treatment of Ni-Co Lateritic Ores for Sustainable Supply of Nickel and Cobalt for European Battery Industry from South-Eastern Europe and Turkey

Srđan Stanković [1,*], Željko Kamberović [2], Bernd Friedrich [3], Srećko R. Stopić [3], Miroslav Sokić [4], Branislav Marković [4] and Axel Schippers [1]

1 Federal Institute for Geosciences and Natural Resources, Stilleweg 2, 30655 Hannover, Germany; axel.schippers@bgr.de
2 Faculty of Technology and Metallurgy, University of Belgrade, 11000 Belgrade, Serbia; kamber@tmf.bg.ac.rs
3 IME Process Metallurgy and Metal Recycling, RWTH Aachen University, Intzestraße 3, 52056 Aachen, Germany; bfriedrich@ime-aachen.de (B.F.); sstopic@ime-aachen.de (S.R.S.)
4 Institute for Technology of Nuclear and Other Mineral Raw Materials, 11000 Belgrade, Serbia; m.sokic@itnms.ac.rs (M.S.); b.markovic@itnms.ac.rs (B.M.)
* Correspondence: srdjan.stankovic@bgr.de; Tel.: +49-(0)511-643-3152

Abstract: The automotive industry is in the process of transformation from the traditional production of vehicles with engines powered by the combustion of fossil fuels to vehicles powered by electric energy. This revolutionary transformation will generate a growing demand for metallic raw materials that are a crucial part of batteries—nickel and cobalt, among others. Providing enough raw materials for e-mobility in a sustainable way will be a challenge in the years to come. The region of South-Eastern Europe (SEE) and Turkey is relatively rich in lateritic Ni-Co deposits, and this region has the potential to partially replace the import of nickel and cobalt intermediates to the European Union from distant overseas locations. Possibilities for the sustainable sourcing of nickel and cobalt from the SEE region are reviewed in this paper, with an overview of the global demand and production of these metals, lateritic mineral resources of SEE, the current status of production, and the prospective development of nickel and cobalt production in this region.

Keywords: laterites; hydrometallurgy; Western Balkans; nickel; cobalt; batteries

Citation: Stanković, S.; Kamberović, Ž.; Friedrich, B.; Stopić, S.R.; Sokić, M.; Marković, B.; Schippers, A. Options for Hydrometallurgical Treatment of Ni-Co Lateritic Ores for Sustainable Supply of Nickel and Cobalt for European Battery Industry from South-Eastern Europe and Turkey. *Metals* **2022**, *12*, 807. https://doi.org/10.3390/met12050807

Academic Editor: Petros E. Tsakiridis

Received: 31 March 2022
Accepted: 4 May 2022
Published: 7 May 2022

1. Introduction

In today's world, the greatest revolution in the automotive industry since the invention of the engine with internal combustion is the transition to cars powered by electric engines. Some leading car manufacturers are announcing a complete transfer to e-mobility in the next ten years, and the EU´s target is to have 30 million electric cars on the roads by 2030 and zero emissions for new cars by 2035 [1]. The increase in the production of electric vehicles has been followed by a dramatically increased demand for batteries. Planned capacities for the production of Li-ion batteries in the EU should be sufficient to supply the EU´s car manufacturers with batteries [2]. Currently, battery manufacturers in the EU heavily rely on the import of raw materials from outside Europe [3]. The transfer to e-mobility is connected to the promise of zero-carbon emissions, so critical metals for the production of batteries, such as nickel and cobalt, need to be extracted in a sustainable way, using technologies with reduced energy consumption and carbon dioxide emissions. The sustainable production of nickel and cobalt from "local" European resources, together with the development of recycling technologies, should reduce the EU's automotive industry's dependence on importing these metals from distant locations and mitigate the risk of supply shortages. Countries in South-Eastern Europe (SEE) and Turkey have significant deposits of nickel- and cobalt-bearing lateritic ores in close proximity to the EU´s industry. Available scientific data on the hydrometallurgical processing of laterites from SEE are often scarce. The aim of this review is to analyze the capacities of the SEE countries to take part in the supply of nickel and cobalt for growing industrial battery production and to attract the attention of the scientific community and potential investors towards the research and development of hydrometallurgical processes for nickel and cobalt production from lateritic ores located in this region.

2. Nickel and Cobalt Market and Production

The total global nickel demand in 2019 was 2.4 million tons (Mt). Most of the nickel was used for the production of stainless steel (71%) and 5% was used for the production of batteries (Figure 1). It is predicted that, in the following years, the nickel market will undergo dramatic changes: the nickel consumption for batteries will increase to 21% of the global demand—62% will be utilized for stainless steel production and 17% for other products [4,5]. The world´s leading nickel producers are located in Southeast Asia and Oceania (Indonesia, Philippines, New Caledonia, Australia); these countries currently produce 60% of nickel. Significant nickel producers are also the Russian Federation, Canada, Brazil, and the EU country Finland. Recently, Indonesia became the world´s leading nickel producer, with an annual production capacity that will reach 2 Mt in the next few years [5].

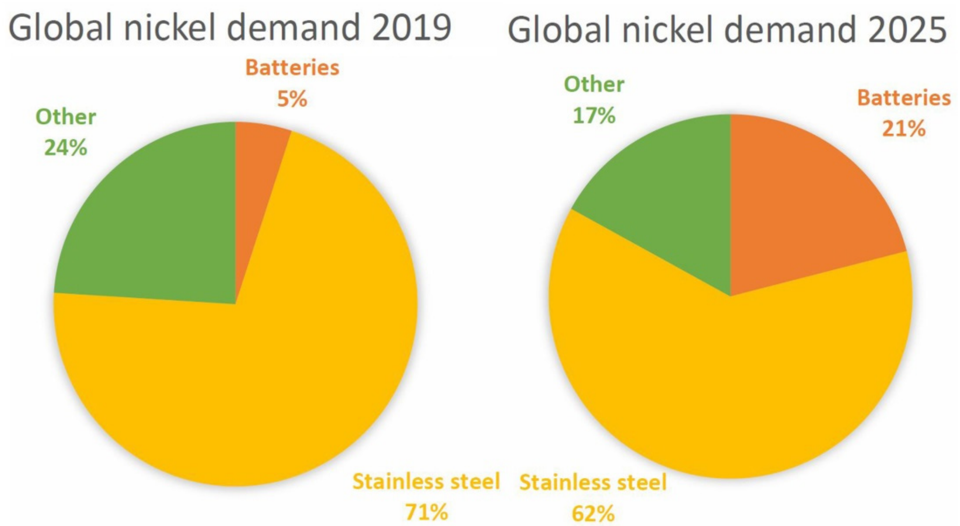

Figure 1. Nickel demand by application [4,5].

The growing nickel demand will be mostly driven by the increasing demand for electric vehicles. Nickel can be produced by pyrometallurgy in ferronickel smelters, or dissolved from nickel-bearing ores using hydrometallurgical approaches. The production of batteries requires nickel sulfate produced from high-purity ($>$ 98.5%) class I nickel products or intermediates such as mixed nickel–cobalt hydroxide (MHP), among others. Class I nickel accounts for roughly half of the global nickel production. Class II products (with purity $<$ 98.5%) ferronickel and nickel pig iron are less suitable for the production of nickel sulfates due to the complex and expensive processing steps for the production of nickel sulfates from these intermediates. Mixed hydroxide products (MHP) and mixed sulfide products (MSP) are the final products of hydrometallurgical nickel extraction. These intermediates are suitable for the cost-effective production of nickel and cobalt sulfates in refineries. The nickel demand for nickel sulfate production is expected to grow globally from 159 kilotons (Kt) of Ni in 2020 to 2 megatons (Mt) of Ni by 2040 (Figure 2) [5].

Cobalt is a rare metal that is almost exclusively produced as a byproduct of the copper and nickel industry. Mines with cobalt as a main metal are located only in the Democratic Republic of Congo and Morocco. The global mine production of cobalt in 2018 reached nearly 168,000 tons, which was the highest annual production so far; approximately 65% of the total cobalt came from the Congo [6]. Other important cobalt producers are Australia (5%), Russia (4%), and the Philippines (4%). Currently, 57% of Co is used for the production of Li-ion batteries. It is estimated that, by 2029, the global industry will require an additional 100,000 t of cobalt, with total consumption of nearly 300,000 tons (Figure 3). The share of cobalt used for the production of batteries will rise to 70% [7,8]. There is concern about working conditions and child exploitation in cobalt mines in the Congo [9]. In addition, it is a politically unstable country, so internal conflicts could jeopardize the cobalt supply. There is a high risk of shortages in cobalt supply in the future; for this reason, the European Commission has placed cobalt on the list of critical raw materials [10].

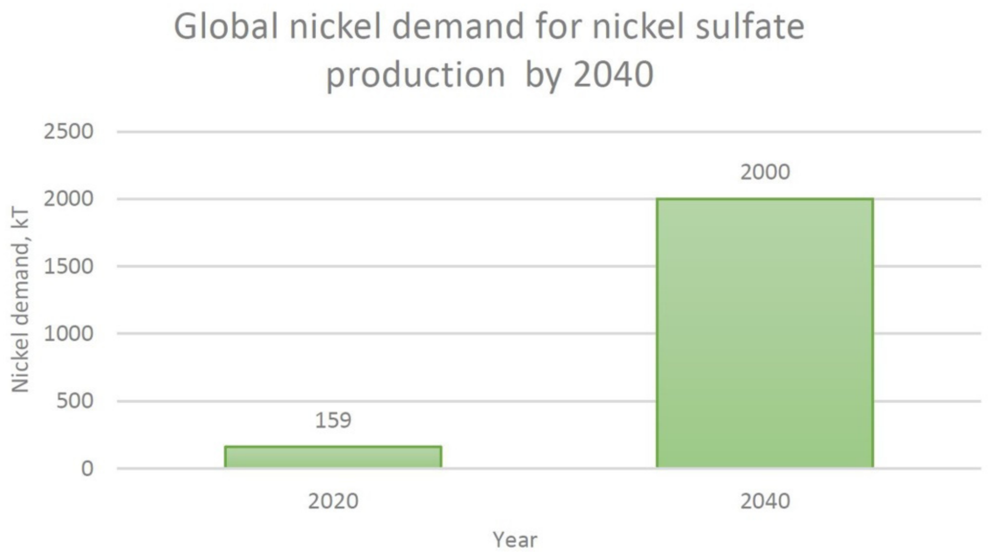

Figure 2. Forecast of the global nickel demand for nickel sulfate production by 2040 [5].

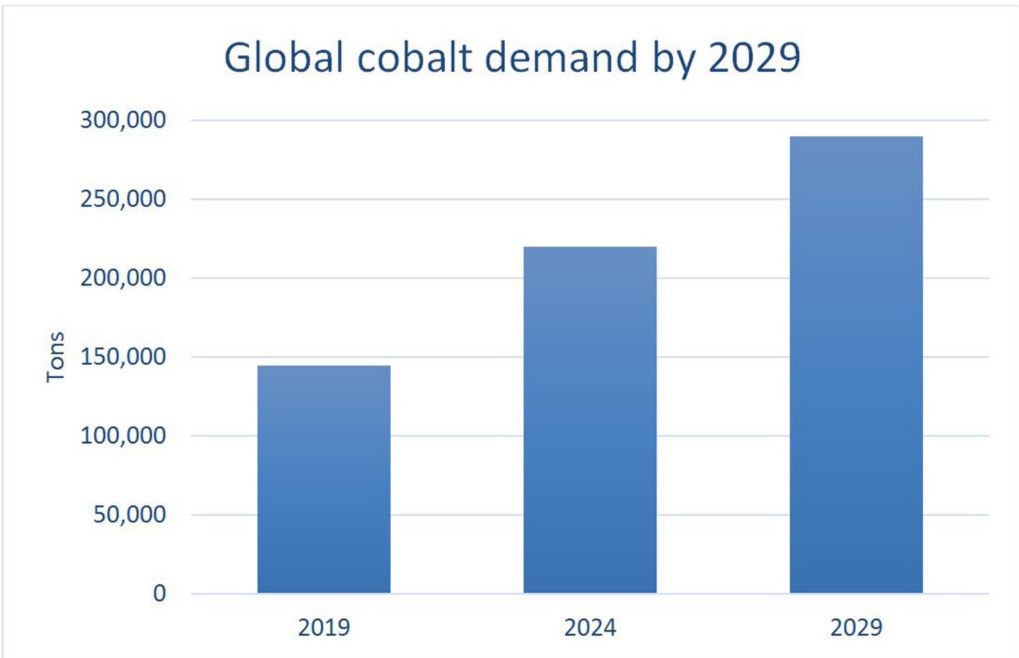

Figure 3. Forecast of the global cobalt demand by 2029 [7,8].

Nickel and Cobalt Resources and Production Capacities in the SEE and Turkey

For many years, nickel and cobalt were predominantly produced pyrometallurgically from sulfide ores. The nickel sulfide ores account for approximately 30% of the global nickel deposits; the rest of the nickel in the Earth's crust is hosted by laterites. It is estimated that, by 2022, approximately 72% of nickel will be extracted from lateritic ores.

Laterites are supergene ore bodies formed by the chemical and mechanical weathering of magmatic (ultramafic) rocks. Lateritic Ni-Co deposits are located mostly in tropical areas, approximately up to 20 degrees north and south of the equator, but some lateritic deposits occur in non-tropical areas in Europe (Balkan Peninsula and Ural Mountains), Asia (Turkey, Kazakhstan), and the USA (Oregon, California, and North Carolina). Lateritic ores usually contain between 0.8 and 3% of nickel and 0.05–0.5% of cobalt [11]. Countries of the SEE (Albania, Bosnia Herzegovina, Greece, Kosovo, North Macedonia, Serbia) and Turkey host significant Ni-Co laterite deposits, which are part of the Eastern and Western Ophiolitic Belts spanning from Bosnia Herzegovina to Iran (Figure 4) [6].

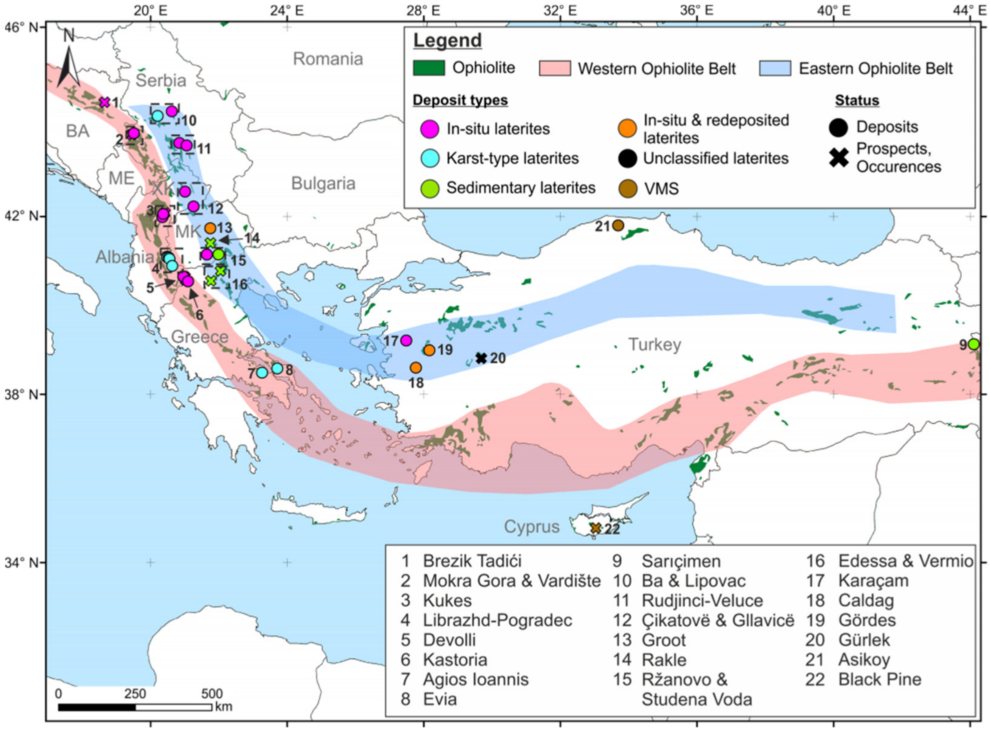

Figure 4. Laterite deposits in the Eastern and Western Ophiolitic Belt. The figure is reproduced from [6].

Laterites originating from the Balkan Peninsula and tropical areas differ significantly. Tropical laterites are a type of soil with a fine grain size, while Balkan laterites are in the form of rock. Nickel laterites in the Balkan Peninsula and Turkey were formed as early as the Early Cretaceous and may be partially preserved in situ or may be transported, partially mixed with bauxites derived from non-ultramafic protoliths, re-deposited as marine sediments and buried by later sedimentary rocks. Some have been lithified and metamorphosed [12]. Table 1 lists the most important deposits of Ni-Co-bearing ores in the SEE and Turkey. The main laterite deposits in Greece are Kastoria, Agios Ioannis, and Evia, owned by the Larco Mining and Metallurgical Company. Albania has the largest nickel deposits in the region, located in three clusters (Kukes, Librazhd-Pogradec, and Devolli), with 1% average nickel content. The Librazhd-Pogradec cluster is dominated by limonitic laterites, while the Kukes and Devolli clusters are rich in saprolite–garnierite ore [13–16]. In comparison to most important global reserves, laterite deposits in the Western Balkans region and Turkey are small to medium in size [17].

Serbia has some smaller laterite deposits in the central and western parts of the country (regions of Šumadija and Western Serbia). The large deposit of low-grade nickel ore Vardište in Bosnia Herzegovina is in close proximity to the largest Serbian Mokra Gora deposit; both deposits are actually part of the larger deposit of the Fe-Ni lateritic ore [13]. Proven reserves of the Vardište deposit are 67 Mt, but it is estimated that there is approximately 200 Mt of low-grade nickel ore [18]. Further geological investigations are required in order to evaluate potential laterite reserves in Bosnia Herzegovina. The major parts of deposits Čikatova and

Glavica in Kosovo and Ržanovo in North Macedonia are already exhausted due to decades of mining, but Kosovo and North Macedonia might have some valuable unexploited deposits [19]. The most important Turkish laterite deposits, Gördes and Çaldağ, are located in the western part of the country. Hydrometallurgical processing of Ni-Co laterites allows the extraction of both nickel and cobalt. Because of cobalt's high market price, the extraction of cobalt has a beneficial effect on the profitability of hydrometallurgical operations. The concentration of cobalt in the laterite deposits of the SEE region is usually around 0.05%. The Brezik-Tadići deposit in Bosnia Herzegovina is unique because it contains proven reserves of 3 Mt of ore with exceptionally high concentrations of cobalt (0.1–0.38%), hosted mostly by asbolane mineral phases, occurring in Fe-oxy-hydroxide-rich units [6].

Table 1. The most important nickel reserves in SEE and Turkey [6,13–16].

Country	Deposit	Ni, %	Ore Reserves, Mt	Ni Content, Mt
Albania	Devolli	1.2	104	1.25
Albania	Has-Kukes-Lure	1.1–1.2	80	0.89
Albania	Librazhd-Pogradec	0.8–1	222	1.8
Bosnia Herzegovina	Vardište	0.8	67	0.54
Greece	Kastoria	1	8.7	0.087
Greece	Agios Ioannis	0.8	43.6	0.35
Greece	Evia	1	228.3	2.28
Kosovo	Čikatova	1.29	4	0.05
Kosovo	Glavica	1.55	6	0.09
North Macedonia	Ržanovo	1.0	10	0.1
North Macedonia	Takovo	1.0	20	0.2
North Macedonia	Rakle	0.4	200	0.8
Serbia	Mokra Gora	0.7–0.8	100	0.75
Serbia	Western Serbia	1.2	30	0.36
Serbia	Šumadija region	0.8	20	0.16
Turkey	Çaldağ	1.1	29.7	0.3
Turkey	Gördes	1	70	0.7

3. Selection of the Most Suitable Hydrometallurgical Technologies for Processing of Ni-Co Lateritic Ores

Table 2 lists the hydrometallurgical technologies for the extraction of Ni and Co from lateritic ores that have been applied on an industrial scale [11,20].

Table 2. Comparison of energy consumption, average carbon dioxide emissions, and capital and operational expenses of the metallurgical operations for nickel production from lateritic ores. Values in brackets for GHG emissions are values for hydrometallurgical operations that do not have acid production plant on site [21–23]. Abbreviations: HPAL—high-pressure acid leaching, AL—atmospheric pressure tank leaching, HL—heap leaching.

Process	Energy Consumption, GJ/t Ni	GHG Emissions, tCO_2/t Ni	CapEx, USD/lb Ni	OpEx, USD/lb Ni
HPAL	272	22.7 (27.3)	49.00	4
AL	167	14.6 (25.1)	25.00	3
HL	211	17.6 (28)	15.00	2
Ferronickel	236	22.4	24.00	2.2

3.1. High-Pressure Acid Leaching (HPAL)

High-pressure acid leaching is a technology based on the sulfuric acid leaching of Ni and Co in autoclaves under elevated temperature and pressure. The process is very efficient: it takes 60–90 min to complete, with Ni and Co recoveries > 95%, and low acid consumption in comparison to other hydrometallurgical operations on laterites (300–400 kg of sulfuric acid per ton of ore). It is a sophisticated technology that often requires several billions of dollars of capital investment and highly skilled engineers to control the process.

Many HPAL operations are facing technical failures and long ramp-up delays, with capital and operational expenses that are significantly higher than planned [24].

3.2. Atmospheric Pressure Tank Leaching (AL)

The limonite and saprolite ores are leached with sulfuric acid in stirred tanks at atmospheric pressure. The process is undertaken at 90–95 °C and the leaching time is up to 12 h. The process can be applied to low-grade ores (<1.5% Ni), and recoveries of Ni and Co are relatively high (>90% for Ni and >80% Co). The main disadvantage of this process is the high acid consumption, usually in the range of 600–800 kg per ton of ore [11].

3.3. Heap Leaching (HL)

This technology is based on the construction of large heaps that are irrigated by sulfuric acid. Recoveries of nickel are in the range of 65–85% over 120–500 days, with acid consumption of 200–500 kg per ton of ore. Relatively low capital and operational expenses are the main advantages of this process, but a slow leaching rate and lower recoveries of Ni and Co in comparison to other technologies are the main disadvantages.

In Table 2, the energy consumption, carbon dioxide emissions, and capital and operational expenses of the metallurgical operations for the production of nickel from the lateritic ores are compared [21,22].

The energy consumption and emissions of greenhouse gases (GHG) of the HPAL process are comparable to those of ferronickel smelters. An important factor that determines the GHG emissions of Ni-Co operations is the source of electric energy (coal combustion, wind, hydropower, etc.). Consumption of sulfuric acid is the most important factor that determines the profitability of the hydrometallurgical processing of the laterites, and the majority of GHG emissions are related to acid neutralization by limestone [22]. The selection of the most appropriate hydrometallurgical technology requires a balance between process efficiency and capital/operational expenses. CapEx and OpEx are lowest for HL operations, and, as they are less complex in comparison to AL and particularly HPAL, there is a lower risk of technical failure for HL. However, not all laterites are suitable for HL—laterites with high iron content usually exhibit low leaching degrees of Ni and Co [25]. Advantages of AL are the high leaching degrees of Ni and Co, moderate CapEx and OpEx, and low energy consumption and GHG emissions. Lateritic ores rich in Mg are not suitable for AL, because the acid consumption is too high, making this process unprofitable. The most robust hydrometallurgical process for the treatment of nickel laterites is HPAL, with low acid consumption and excellent process efficiency for almost every ore sample, including refractory iron-rich limonitic ores. The average CapEx and OpEx of the HPAL operations are highest in comparison to other technologies. As a complex metallurgical process, HPAL is facing many challenges, and technical failures have been reported [24]. A comparison of hydrometallurgical technologies for the extraction of Ni and Co from lateritic ores that have been applied on an industrial scale is given in Table 3.

Table 3. Comparison of hydrometallurgical technologies for extraction of Ni and Co from lateritic ores that have been applied on an industrial scale [11,20].

Process	CapEx	OpEx	Acid Consumption	GHG Emission	Energy Consumption	Ni and Co Extraction [%]
HPAL	High	Mode-rate	Low	High	High	90–95
HL	Low	Low	Moderate	Moderate	Moderate	70–80
AL	Mode-rate	Mode-rate	High	Low	Low	85–95

4. Current Ni Production from Laterite Deposits in SEE and Turkey

Albania has been mining nickel ores for decades, but there are no processing facilities; thus, Albania exports only the lateritic ore. Bosnia Herzegovina and Serbia have significant Ni-Co deposits, but there are no nickel mining or laterite processing facilities in these countries either. Kosovo, North Macedonia, and Greece have mines and ferronickel smelters.

The first hydrometallurgical plant in this region for the production of Ni and Co from lateritic ores was commissioned in the Gördes mine in Turkey, and recently, the Hellenic Minerals Company started production of nickel and cobalt sulfates from laterites imported from Africa. An overview of the industrial facilities for the processing of laterites in the SEE and Turkey is given in Table 4.

Table 4. Industrial facilities for processing of laterites in the SEE and Turkey region. Data presented in Figure 4 are collected from the official corporate websites.

Company	Country	Technology	Main Product	Annual Ni Production Capacity [t]
NewCo Feronikeli	Kosovo	Smelting	Ferronickel	7500
Euronickel	North Macedonia	Smelting	Ferronickel	20,000
Larco	Greece	Smelting	Ferronickel	20,000
Meta Nickel	Turkey	HPAL	MHP	20,000 (planned)
Çaldağ	Turkey	AL	Ni, Co	16,000 (planned)
Hellenic Minerals	Cyprus	AL	$NiSO_4$	50,000 (planned)

The SEE's ferronickel industry has difficulty competing with huge and more efficient ferronickel and particularly nickel pig iron producers worldwide. Ferronickel producers in this region often face financial problems and the profitability of these companies is very sensitive to drops in nickel prices.

Over the years, a significant amount of data about the application of hydrometallurgy for the processing of Greek laterites have been accumulated [25–27]. Agatzini-Leonardou et al. [28] examined AL and HL in the columns of serpentinic laterite samples from the Kastoria mine in Greece. HL tests in columns showed 60% Ni extraction and 45% Co extraction in 10 days, with acid consumption of 400 kg/t. Maximal Ni and Co extractions after AL were 74% and 51%, respectively, with acid consumption of 550 kg/t. Agatzini-Leonardou et al. [28] examined the pilot-scale heap leaching of 800 tons of lateritic ore from the "Triada" deposit in Greece, owned by Larco. The ore contained 35.6% Fe, 0.73% Ni, and 0.06% of Co. The leaching agent was 2N sulfuric acid and the leaching duration was 114 days; the leaching degrees of Ni and Co were 60% and 36%, respectively, with acid consumption of 660 kg sulfuric acid per ton of ore. More recently, Komnitsas et al. [26,27] examined HL in columns of low-grade lateritic ore from the Agios Ioannis mine in Greece. The leaching degree of Ni was 60% with 1.5 M sulfuric acid, but it increased to 80% after the addition of the reducing agent Na_2SO_3, with acid consumption of 688.8 kg/t.

The development of hydrometallurgical technologies for nickel and cobalt production from the Çaldağ and Gördes lateritic deposits in Turkey is a result of extensive research conducted by Turkish universities [29–32]. Kaya and Topkaya [29] examined HPAL of the limonitic ore from the Gördes mine in Turkey and determined Ni extraction of 87.3% and Co extraction of 88.8%, with acid consumption of 300 kg/t. Oxley et al. [30] described the Çaldağ nickel heap leach trial plant, demonstrating the leachability of Çaldağ nickel laterites using an atmospheric heap leaching process (HL) with sulfuric acid. The leach cycle of the first heap (average of Çaldağ deposit) was completed after 548 days, with extractions of 79.4%, 82.7%, and 30.0%, for nickel, cobalt, and iron, respectively. The acid consumption for neutralization and the primary and secondary stages of leaching per ton of dry ore was calculated as 35 kg, 116 kg, and 377 kg. This resulted in approximately 80% of nickel extraction.

After AL of the Çaldağ ore, over 90% of Ni and Co was extracted [31,32]. Table 5 shows a summary of the cited literature data on the hydrometallurgical processing of laterites from the SEE and Turkey.

Table 5. Overview of the selected literature data on laboratory-scale experiments for leaching of lateritic ores from SEE and Turkey.

Deposit	Country	Technology	Ni Extraction [%]	Acid Concentration	Temperature, °C	Leaching Duration	Acid Consumption [kg/t]	References
Agios Ioannis	Greece	HL + Na_2SO_3	80	1.5 M + 20 g/L Na_2SO_3	Ambient	33 days	688	[26,27]
Ba	Serbia	HPAL	85	210 g/L	220–240	120 min	/	[33]
Çaldağ	Turkey	HL	80	1 M	Ambient	548 days	510	[30]
Çaldağ	Turkey	AL	90	2 M	90	6 h	/	[31]
Devolli	Albania	HL	80	75 g/L	Ambient	200 days	500	[34]
Gördes	Turkey	HPAL	87	300 g/L	245–270	90 min	300	[29,35]
Kastoria	Greece	HL	60	3 N	Ambient	18 days	400	[25]
Kastoria	Greece	AL	74	3 N	80	120 min	550	[25]
Lipovac	Serbia	HPAL	37	210 g/L	220–240	120 min	/	[33]
Ruđinci	Serbia	AL	78	0.4 M	90	120 min	/	[36]
Ruđinci	Serbia	HPAL	95	210 g/L	220–240	120 min	/	[33,37,38]
Ržanovo	N. Macedonia	AL	85	3 M	90	120 min	/	[39]
Ržanovo	N. Macedonia	AL + ultrasound	91	3 M	75	150 min	/	[40]
Triada	Greece	HL	60	100 g/L	Ambient	114 days	660	[28]

Available data on the hydrometallurgical processing of laterites from the Western Balkans region (Albania, Bosnia Herzegovina, Kosovo, and Serbia) are very limited, and important data, such as acid consumption, are often missing in scientific reports. There were several scientific papers on the hydrometallurgical processing of Serbian laterites published from the 1980s until beginning of the 2000s, which focused on the application of the HPAL and AL technologies [41,42]. Stopić et al. [36] investigated the leaching of the laterite ore from the Rudjinci deposit (Serbia, Western Morava region) with sulfuric acid at atmospheric pressure. The highest leaching degree of 78% of Ni was achieved at 90 °C with 0.4 mol/L sulfuric acid. Matković et al. [37] examined the leaching of nickel ore from the Ruđinci deposit with sulfuric acid, at elevated temperatures and pressure, in an autoclave. The nickel leaching degree was 95% at a temperature of 240 °C, pressure of 3.3 Mpa, and a sulfuric acid concentration of 210 g/L. Stopić et al. [38] studied the extraction of nickel from Serbian and Western Australian lateritic ores by sulfuric acid leaching under high pressure. The target values of 95% Ni extraction and 60% Co extraction were achieved in 5 min at 250 °C for the Serbian silicate ore, at an agitation rate of 1500 rpm, 10% solids, and an acid/ore ratio of 0.40. Under similar conditions, only 60% Ni and 69% Co could be extracted from an Australian ore due to differences in mineralogy. Kamberović et al. [33] tested the high-pressure acid leaching of ores from the deposits Ruđinci, Ba (Western Serbia region, laterite ore), and Lipovac (Šumadija region, sulfide ore). Nickel extraction from the Lipovac sulfide ore was very low, even after the addition of oxidizing agents (H_2O_2 and HNO_3)—the leaching efficiencies were 16% and 37%, respectively. The maximal leaching degree for a lateritic sample from the Ba deposit was 85%. The best results were obtained after the leaching of an ore from the Ruđinci deposit, where the Ni extraction was 95%. Information on the hydrometallurgical processing of Albanian laterites is very scarce. Russell [34] tested the column leaching of saprolitic and limonitic laterites from the deposit in the Devolli region in Albania. The author reported approximately 80% of nickel recovery after 154 days from an agglomerated mixed ore (50% saprolitic ore, 50% limonitic ore), with acid consumption of 500 kg/t of ore. Petrovski et al. [39] tested the leaching of Ni from low-grade lateritic ores originating from the North Macedonian Ržanovo mine (0.8% Ni). The highest Ni extraction of 85% was achieved with 3M sulfuric acid at 90 °C after 120 min of leaching. Paunović et al. [40] tested the ultrasound-enhanced leaching of an ore from the same Ržanovo deposit. A maximal leaching degree of 91% was achieved with 3 M sulfuric acid, a temperature of 75 °C, and the application of ultrasound. To the best of our knowledge, there is no information on the hydrometallurgical processing of laterites from Bosnia Herzegovina.

The process of technology selection for the hydrometallurgical processing of laterites can be illustrated by an investigation of the most suitable process for the treatment of lateritic ore from the Gördes deposit. Two types of ores were tested: an iron-rich limonitic ore and a clay-rich nontronite ore. Table 6 presents the results of HL, AL, and HPAL of the Gördes ore [35].

Table 6. Process selection for Gördes laterite deposit [35].

Process	Ore Type	Acid kg/t	Leaching Time	Ni Extracted [%]	Co Extracted [%]
AL	Nontronite	856	5 h	93	77
	Limonite	907	24 h	85	87
HL	Nontronite	462	144 days	84	55
	Limonite	560	534 days	65	57
HPAL	Nontronite	536	90 min	98	94
	Limonite	300	90 min	89	90
	Blend	315	60 min	90	97

The clay-rich (nontronite) ore was more easily leachable than the iron-rich limonitic ore. Results of AL showed the high extraction of Ni and Co, but with huge acid consumption (856 kg/t and 907 kg/t for nontronite and limonite ore, respectively). HL was successful for the nontronite ore, but leaching of the limonitic ore produced unsatisfactory results, with 65% of Ni leached during a very long period of 534 days. HPAL experiments produced excellent recovery of Ni and Co, with the lowest acid consumption and a short leaching time. Leaching of blended limonite and nontronite ore at pilot scale was successful, with Ni and Co recoveries of 90% and 97%, respectively. Due to the high process efficiency and low acid consumption, HPAL was selected as the most suitable technology for the processing of the laterite ore from the Gördes deposit. AL is not a suitable process due to its high acid consumption, and HL is not suitable because of its inefficient Ni recovery from limonitic ore and relatively low Co recovery.

Emerging technologies, such as bioleaching of the laterites, may become important in the years to come. Finland is currently Europe's most important nickel and cobalt producer. The Finish company Terrafame extracts Ni, Co, Cu, and Zn from sulfide minerals contained in the black schist ore using heap bioleaching technology. Nickel and cobalt sulfides, which are the final products of the bioleaching and downstream processes, are transported to a recently opened refinery for the production of battery-grade nickel and cobalt sulfate. The company claims that the average CO_2 emissions are only 1.75 kg per kg of nickel sulfate produced. This is a result of the use of heap bioleaching technology, which consumes up to 90% less electricity and heat in comparison to other technologies [43,44]. An option for the processing of laterites from the SEE might be bioleaching using acidophilic bacteria, which oxidize added elemental sulfur to sulfuric acid, thereby reducing and/or dissolving Fe(III) and Mn(IV) minerals in the lateritic ore; however, this approach has so far only been successfully tested at a laboratory scale [45,46]. The direct nickel process is a patented technology for the treatment of laterites that has been successfully tested on a pilot scale, but it is still not applied on an industrial scale. The technology is based on the leaching of limonitic and saprolitic laterites by nitric acid at a temperature of 110 °C and atmospheric pressure. The process is very efficient, with over 90% of nickel extraction in 2–4 h and low acid consumption of 30–80 kg per ton of ore, due to the innovative technology that allows the recycling of the nitric acid in the process. The Neomet process is another innovative solution for laterite processing that has not been applied on an industrial scale yet. This process is based on leaching with hydrochloric acid at temperatures of 100–110 °C and atmospheric pressure. Leaching efficiency is high, with over 95% of nickel extracted, while acid consumption is low due to the regeneration of the hydrochloric acid in the process [11].

5. Conclusions

Countries of the SEE and Turkey have substantial potential to supply nickel and cobalt for the European battery industry, but more research activities are required, particularly in the countries of the Western Balkans region. Turkey is a good example of how investment in research and development can lead to the actual processing of laterites in modern hydrometallurgical plants. Albania has carried out the mining of laterites for decades and possesses substantial ore reserves, but processing facilities are lacking. Research on the processing of Albanian laterites can lead to the development of new hydrometallurgical plants. In spite of extensive research conducted by universities in Greece, there is still no plant for the hydrometallurgical processing of laterites in this country. Approximately ten years ago, there was an attempt of the Serbian government to initiate nickel mining in Serbia. This attempt was unsuccessful due to the strong resistance of environmental NGOs, local communities, and academia. The largest Serbian deposit, Mokra Gora, is located in a protected area of nature, in close proximity to the Tara National Park and River Drina. Regions of Western Serbia and Šumadija host smaller nickel deposits, which are located in populated agricultural areas with vineyards and orchards. Therefore, nickel mining in Serbia is probably not a feasible option. Bosnia Herzegovina hosts some promising deposits of Ni and Co ores, but there is no available scientific information about processing options for these ores.

Identification of the most appropriate hydrometallurgical processing technology for particular laterite deposits, and optimization of the leaching and recovery of metals from the pregnant leach solution, including environmental impact assessment, requires intensive research work and substantial financial investments. Meta Nickel, Gördes has shown high potential for the production of mixed nickel–cobalt hydroxide. The demonstration plant at Çaldağ has proven that nickel and cobalt can be extracted by means of atmospheric heap leaching and that a saleable product can be produced. Intensive research activities are crucial for the countries of the region to convert their mining and metallurgical industry from producers of raw materials and products, that are not competitive on the global market (ferronickel), to an industry that implements sophisticated hydrometallurgical technologies with reduced capital and operational expenses in order to produce high-quality final products and to ensure a sustainable supply for battery manufacturers.

Author Contributions: Conceptualization and writing—original draft preparation, S.S.; writing, review and editing, Ž.K., B.F., S.R.S. and M.S.; review, editing and technical preparation of the manuscript, B.M.; review, editing and supervision A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to Michael Szurlies from the Federal Institute for Geosciences and Natural Resources (BGR) and Herwig Marbler from the German Mineral Resources Agency (DERA) within BGR for improving the manuscript with their valuable comments. The authors are also grateful to Stefan Horn from the British Geological Survey (BGS) for providing the high-resolution image of the laterite deposits in the Balkans and Turkey (Figure 4).

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

References

1. Euractiv Official Web Site. EU to Target 30 Million Electric Cars by 2030. 2020. Available online: https://www.euractiv.com/section/electric-cars/news/eu-to-target-30-million-electric-cars-by-2030-draft/ (accessed on 7 August 2021).
2. Euractiv Official Web Site. EU Says It Could Be Self-Sufficient in Electric Vehicle Batteries by 2025. 2020. Available online: https://www.euractiv.com/section/batteries/news/eu-says-it-could-be-self-sufficient-in-electric-vehicle-batteries-by-2025/ (accessed on 7 August 2021).

3. Euractiv Official Web Site. Raw materials: The Missing Link in Europe's Drive for Batteries. 2020. Available online: https://www.euractiv.com/section/energy-environment/news/raw-materials-the-missing-link-in-europes-drive-for-batteries/ (accessed on 7 August 2021).
4. Szurlies, M.; Deutsche Rohstoffagentur Official Web Site. Rohstoffrisikobewertung–Nickel, 48 DERA Rohstoffinformationen, S.; Berlin. 2021. Available online: https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-48.pdf;jsessionid=B4EFF1139CE65624C37A8B819DC51508.1_cid284?__blob=publicationFile&v=4 (accessed on 29 August 2021). (In German)
5. Fraser, J.; Anderson, J.; Lazuen, J.; Lu, Y.; Heathman, O.; Brewster, N.; Bedder, J.; Masson, O. *Study on Future Demand and Supply Security of Nickel for Electric Vehicle Batteries*; Publications Office of the European Union: Luxembourg, 2021. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC123439 (accessed on 10 September 2021). [CrossRef]
6. Horn, S.; Gunn, A.G.; Petavratzi, E.; Shaw, R.A.; Eilu, P.; Törmänen, T.; Bjerkgård, T.; Sandstad, J.S.; Jonsson, E.; Kountourelis, S.; et al. Cobalt resources in Europe and the potential for new discoveries. *Ore Geol. Rev.* **2021**, *130*, 103915. [CrossRef]
7. BGR Official Web Site. Batterierohstoffe für die Elektromobilität, DERA Themenheft: 26 S. Berlin. 2021. Available online: https://www.bgr.bund.de/DERA/DE/Downloads/DERA%20Themenheft-01-21.pdf?__blob=publicationFile&v=6 (accessed on 25 September 2021). (In German)
8. Al Barazi, S.; Deutsche Rohstoffagentur Official Web Site. *Rohstoffrisikobewertung–Kobalt. DERA Rohstoffinformationen 36: 120 S. Berlin*. 2018. Available online: https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-36.pdf?__blob=publicationFile&v=2 (accessed on 25 September 2021). (In German)
9. Al Barazi, S.; Näher, U.; Vetter, S.; Schütte, P.; Liedtke, M.; Baier, M.; Franken, G.; Deutsche Rohstoffagentur Official Web Site. Cobalt from the DRC–Potenital, Risks and Significance for the Global Cobalt Market, Comoditiy Top News v. 53, Hannover, 2017. Available online: https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/Commodity_Top_News/Rohstoffwirtschaft/53_kobalt-aus-der-dr-kongo_en.pdf?__blob=publicationFile&v=6 (accessed on 21 August 2021). (In German)
10. European Commission Official Web Site. Study on the EU's list of Critical Raw Materials. 2020. Available online: https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf (accessed on 22 September 2021).
11. Stanković, S.; Stopić, S.; Sokić, M.; Marković, B.; Friedrich, B. Review of the past, present, and future of the hydrometallurgical production of nickel and cobalt from lateritic ores. *Metall. Mater. Eng.* **2020**, *26*, 199–208. [CrossRef]
12. Eliopoulos, D.G.; Economou-Eliopoulos, M.; Apostolikas, A.; Golightly, J.P. Geochemical features of nickel-laterite deposits from the Balkan Peninsula and Gordes, Turkey: The genetic and environmental significance of arsenic. *Ore Geol. Rev.* **2012**, *48*, 413–427. [CrossRef]
13. Monthel, J.; Vadala, P.; Leistel, J.M.; Cottard, F.; Ilic, M.; Strumberger, A.; Tosovic, R.; Stepanovic, A. Mineral deposits and mining districts of Serbia. Compilation map and GIS databases, BRGM/RC-51448-FR. 2002. Available online: http://gras.org.rs/wp-content/uploads/2017/10/mineral-deposits-and-mining-districts-of-serbia.pdf (accessed on 25 September 2021).
14. Berger, V.I.; Singer, D.A.; Bliss, J.D.; Moring, B.C.; Geological Survey Official Web Site. *Ni-Co Laterite Deposits of the World-Database and Grade and Tonnage Models. 2011-1058*; U.S. Geological Survey: Reston, VA, USA, 2011; 30p. Available online: http://pubs.usgs.gov/of/2011/1058/ (accessed on 28 September 2021).
15. Reseerve Official Web Site. West Balkan Mineral Register of Primary Raw Materials. Available online: https://reseerve.eu/results/west-balkan-mineral-register-of-primary-raw-materials (accessed on 3 September 2021).
16. Japan International Cooperation Agency. The Study for the Master Plan for Promoting Mining Industry in Albania–Final Report 2010. Available online: https://openjicareport.jica.go.jp/pdf/12010138_01.pdf (accessed on 21 September 2021).
17. Elias, M. Nickel laterite deposits–geological overview, resources and exploitation. In *Giant Ore Deposits: Characteristics, Genesis and Exploration*; Cooke, D.R., Pongratz, J., Eds.; CODES Special Publication 4, Centre for Ore Deposit Research, University of Tasmania: Hobart, Australia, 2016; pp. 205–220. Available online: https://www.researchgate.net/publication/281422746_Nickel_laterite_deposits_-_geological_overview_resources_and_exploitation (accessed on 25 April 2022).
18. Serbia Energy Official Web Site. BiH: Vardiste Conceals Million Tons of Nickel; the Obstacle is Environmental Pollution Risks. 2013. Available online: https://serbia-energy.eu/bih-vardiste-conceals-million-tons-of-nickel-the-obstacle-is-environmental-pollution-risks/ (accessed on 3 October 2021).
19. Serafimovski, T.; Boev, B.; Tasev, G. Some quantitative aspects of the major types of ores at the Ržanovo Fe-Ni lateritic deposit, R. Macedonia. *Geol. Maced.* **2012**, *26*, 21–35.
20. McDonald, R.G.; Whittington, B.I. Atmospheric acid leaching of nickel laterites review Part, I. Sulphuric acid technologies. *Hydrometallurgy* **2008**, *91*, 35–55. [CrossRef]
21. Norgate, T.; Jahanshahi, S. Assessing the energy and greenhouse gas footprints of nickel laterite processing. *Miner. Eng.* **2011**, *24*, 698–707. [CrossRef]
22. Gabb, J. HPAL: Upping the Pressure. Global Mining Research, March 2018. Available online: www.globalminingresearch.com (accessed on 15 July 2019).
23. Watling, H.R.; Elliot, A.D.; Fletcher, H.M.; Robinson, D.J.; Sully, D.M. Ore mineralogy of nickel laterites: Controls on processing characteristics under simulated heap-leach conditions. *Aust. J. Earth Sci.* **2011**, *58*, 725–744. [CrossRef]
24. Oxley, A.; Smith, M.E.; Caceres, O. Why heap leach nickel laterites? *Miner. Eng.* **2016**, *88*, 53–60. [CrossRef]

25. Agatzini-Leonardou, S.; Zafiratos, I.G. Beneficiation of a Greek serpentinic nickeliferous ore Part II. Sulphuric acid heap and agitation leaching. *Hydrometallurgy* **2004**, *74*, 267–275. [CrossRef]
26. Komnitsas, K.; Petrakis, E.; Pantelaki, O.; Kritikaki, A. Column leaching of Greek low-grade limonitic laterites. *Minerals* **2018**, *8*, 377. [CrossRef]
27. Komnitsas, K.; Petrakis, E.; Bartzas, G.; Karmali, V. Column leaching of low-grade saprolitic laterites and valorizaton of leaching residues. *Sci. Total Environ.* **2019**, *665*, 347–357. [CrossRef] [PubMed]
28. Agatzini-Leonardou, S.; Oustadakis, O.; Dimaki, D.; Zafiratos, J.; Tsarikidis, P.; Karidakis, T.; Frogoudakis, E.; Drougas, J. Heap leaching of Greek low grade nickel oxide ores by diluted sulphuric acid at a pilot-plant scale. *Mater. Proc.* **2021**, *5*, 65.
29. Kaya, Ş.; Topkaya, Y.A. High pressure acid leaching of a refractory lateritic nickel ore. *Miner. Eng.* **2011**, *24*, 1188–1197. [CrossRef]
30. Oxley, A.; Sirvanaci, N.; Purkiss, S. Çaldağ nickel atmospheric heap leach project. *Metalurgija* **2007**, *13*, 1.
31. Kursunoglu, S.; Kaya, M. Atmospheric pressure acid leaching of Çaldağ lateritic nickel ore. *Int. J. Miner. Process.* **2016**, *150*, 1–8. [CrossRef]
32. Kursunoglu, S.; Ichlas Tanlega, Z.; Kaya, M. Leaching method selection for Çaldağ lateritic nickel ore by the analytic hierarchy process (AHP). *Hydrometallurgy* **2017**, *171*, 179–184. [CrossRef]
33. Kamberović, Ž.; Korać, M.; Anđić, Z.; Uljarević, J.; Mihajlović, A.; Vučurović, D. Technological and environmental aspects of nickel production in Serbia. *Metall. Mater. Eng.* **2014**, *20*, 275–284. [CrossRef]
34. Russell, N. Optimization of Mining and Processing for an Albanian Nickel-Laterite Mine. Master's Thesis, Delft University of Technology, Delft, The Netherlands, June 2011.
35. Stopic, S.; Friedrich, B. Hydrometallurgical processing of nickel lateritic ores. *Mil. Tech. Currier* **2016**, *64*, 1033–1047. [CrossRef]
36. Stopić, S.; Friedrich, B.; Fuchs, R. Sulphuric acid leaching of the Serbian nickel lateritic ore. *Erzmetall* **2003**, *56*, 198–203.
37. Matković, V.; Vučković, N.; Sokić, M.; Stojanović, J.; Marković, B. Investigation of the Processing Possibilities of Nickel Silicate Ore by Acid Pressure Leaching. *Acta Metall. Slovaca* **2004**, *10*, 189–195.
38. Stopić, S.; Friedrich, B.; Anastasijević, N. Kinetics of high pressure leaching of the nickel lateritic ore. In *Proceedings of the Pressure Hydrometallurgy 2004, 34th Annual Hydrometallurgy Meeting of CIM, Banff, AB, Canada, 23–27 October 2004*; Collins, M.J., Papangelakis, V.G., Eds.; Metallurgical Society of the Canadian Institute of Mining, Metallurgy and Petroleum: Banff, AB, Canada, 2004; pp. 247–258.
39. Petrovski, A.; Načevski, G.; Dimitrov, A.T.; Paunović, P. Kinetic models of nickel laterite ore leaching process. *Mach. Technol. Mater.* **2019**, *13*, 487–490.
40. Paunović, P.; Načevski, G.; Petrovski, A.; Tomova, A.; Grozdanov, A.; Dimitrov, A.T. Kinetic analysis of ultrasound leaching of nickel laterite ore. *Bulg. Chem. Commun.* **2019**, *51*, 12–18.
41. Vučurović, D. *Study of Possibility of Nickel Valorisation from Its Ore in Serbia–Report*; University of Belgrade, Faculty of Technology and Metallurgy: Belgrade, Serbia, 1983. (In Serbian)
42. Vučurović, D.; Ilić, I.; Stopić, S. Investigation of optimum conditions for the leaching of nickel ores by ammonia carbonate for nickel extraction. *Metall. Mater. Eng.* **1995**, *1*, 53–67. (In Serbian)
43. Terrafame Official Web Site. Creating Responsible Battery Vale chain, Sustainability Review–June 2021. Available online: https://www.terrafame.com/media/vuosikertomukset/2021/terrafame-sustainable-review-june-2021.pdf (accessed on 9 November 2021).
44. Riekkola-Vanhanen, M. Talvivaara mining company–From a project to a mine. *Miner. Eng.* **2013**, *48*, 2–9. [CrossRef]
45. Johnson, D.B.; Plessis, C.A. Biomining in reverse gear: Using bacteria to extract metals from oxidised ores. *Miner. Eng.* **2015**, *75*, 2–5. [CrossRef]
46. Marrero, J.; Coto, O.; Goldmann, S.; Graupner, T.; Schippers, A. Recovery of nickel and cobalt from laterite tailings by reductive dissolution under aerobic conditions using *Acidithiobacillus* species. *Environ. Sci. Technol.* **2015**, *49*, 6674–6682. [CrossRef] [PubMed]