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# Environmental Sustainability and Supply Resilience of Cobalt

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**Abstract:** Cobalt (Co) is an essential metal for the development of energy-transition technologies, decarbonising transportation, achieving several sustainable development goals, and facilitating a future net zero transition. However, the supply of Co is prone to severe fluctuation, disruption, and price instabilities. This review aims to identify the future evolution of Co supply through technologically resilient and environmentally sustainable pathways. The work shows that advances in both primary and secondary sources, Co mining methods and recycling systems are yet to be fully optimised. Moreover, responsible sourcing from both large mines and small artisanal mines will be necessary for a resilient Co supply. Regulatory approaches may increase transparency, support local mining communities, and improve secondary Co recovery. Novel Co supply options, such as deep-sea mining and bio-mining of tailings, are associated with major techno-economic and environmental issues. However, a circular economy, keeping Co in the economic loop for as long as possible, is yet to be optimised at both regional and global scales. To achieve environmental sustainability of Co, economic incentives, regulatory push, and improved public perception are required to drive product innovation and design for circularity. Although the complexity of Co recycling, due to lack of standardisation of design and chemistry in batteries, is an impediment, a sustainable net zero transition using Co will only be possible if a reliable primary supply and a circular secondary supply are established.

**Keywords:** cobalt; resource sustainability; circular economy; electric vehicles; rechargeable batteries

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## 1. Introduction

Cobalt (Co) is a technologically important metal, with unique properties [1]. Lithium cobalt oxide ($LiCoO_2$) and its derivatives are commonly used as the positive electrode in lithium-ion batteries. This has an ordered laterite structure, with ions situated in well-defined positions stabilised by Co. This results in longer and safe battery life [2]. Co is also found in high performance metal alloys used in jet engines, and in cutting and grinding tools. It is used in desulphurisation catalysts, in digital storage devices, semiconductors and in hydrogen production [3–6]. It therefore has a key role in delivering the technologies required for a net zero transition and is essential to achieve several Sustainable Development Goals (SDGs) [7]. Its use in energy storage systems is important in stabilising renewable energy grids, decarbonising electric mobility systems, and in mitigating climate change [8].

For Co to help reduce national-level greenhouse gas emissions by 2050, uninterrupted supply of Co will be required [9,10]. Thus, Co must remain economically and technologically viable for large-scale deployment [11] and potential use in decarbonising transport, renewable power generation, and provision of electricity to off-grid communities [12].

It is estimated that there are 25 million tonnes of terrestrial Co. The largest and highest-grade Co deposits are in stratiform sediments hosted in Cu-Co deposits [13]. Magmatic Ni-Cu-Co sulphides are available in large quantities. Co is also found in high grade metasedimentary-hosted rocks, including Ni-Co laterites. It is classified as a 'critical raw material' in the EU and as a 'strategically important element' in the USA [14]. Most Co resources are in the Central African copper belt, where ores contain between 0.6 and 1.1 wt.% Co [15]. There are also significant Co-rich resources in Fe-Mn rich ores and metallic nodules found in oceans [16]. Approximately 63 wt.% of mined ores containing Co are in stratiform sediment hosted deposits, with ~20 wt.% in laterites, ~14 wt.% in magmatic sulphides and ~3 wt.% in polymetallic rich veins. Estimated Co-contained reserves are about 7.1 million tonnes, with ~51% located in the Democratic Republic of the Congo (DRC) [17] and in 2019 69.4% of globally mined Co (~144,000 tonnes) was from the DRC [18].

Most Co is produced as a by-product of Cu production, with 20 wt.% as a by-product of Ni production, and 8 wt.% from either Cu or Ni operations. Only about 2 wt.% comes from specific Co mines found in Morocco [13]. Annual production of Co has been increasing at a rate of ~7% in recent years [19], with only a ~0.6% decrease in consumption in 2020 despite the COVID-19 pandemic [20]. Total Co production from refineries was ~132,000 tonnes in 2019 (i.e., cobalt refined from ores, concentrates, or intermediate products), with 68.2% production taking place in China [18]. Around 36% of refined Co production originates from imported materials, as some refining countries, such as Japan and Norway, do not mine Co domestically while countries like China and Finland mainly refine imported Co-containing minerals [18,21]. With complex, yet less diverse supply chains, any potential problems with either Copperbelt mines in Central Africa or Co refineries in China would seriously disrupt the global Co supply [22]. Although there are more than 150 known Co deposits that are yet to be exploited globally, these are not expected to solve supply problems in the medium-to-long term [19,23].

The Co used in lithium-ion batteries accounted for 57% of the total used in 2020, following a 10% annual growth rate between 2013 and 2020 [20]. Other than batteries in automotive and portable electronics, Co was also used in aerospace, energy infrastructure, paints and coatings, machinery and plastics [20]. With rapid growth of EV sales expected in the future, the demand of Co is predicted to increase by a factor of ~20 by 2050 [24], predominantly in the form tetroxides and sulphates of Co [20]. To meet the future Co demand for EVs alone, a minimum of 3% annual supply growth will be necessary [25]. Current consumption data shows that Asia is the largest market for Co, followed by Europe and North America [17]. However, long-term deals, generous subsidies, and incentives in Europe have helped to attract investors to secure and buffer stocks, initiate new export routes and improve price security as the market matures.

Extensive research is ongoing to reduce or replace Co in cathodes [26]. However, this is not currently possible, due to various technical challenges and safety concerns. Reducing the amount of Co in each battery could be possible, but the reduction in Co use per battery is likely to be outweighed by the significantly high number of batteries required in the future [27]. Therefore, Co supply must evolve to prevent major barriers to achieving many desirable environmental and energy transitions.

The following sections will discuss how the supply of Co needs to evolve to be both technologically resilient and environmentally sustainable. In this regard, we discuss the current status of Co extraction and refining in Section 2, responsible Co sourcing and mining including its environmental and social implications in Section 3, alternative extraction techniques for low-grade Co extraction such as by phyto-mining and bioleaching in Section 4, and the potential development of Co circular economy based on secondary extraction and recycling in Section 5. The main conclusions are presented in Section 6.

## 2. Cobalt Extraction, Processing, and Refining

About 51% of global Co reserves are in the DRC, which is reported to be the 6th most fragile country and the 17th most corrupt country in the world [28]. Amnesty International regard Co as a 'conflict mineral', that is traded, taxed, and looted, fuelled by corruption, and sourced under hazardous working conditions that violate human rights [29]. However, only about 10% of DRC mines are illegal and fall under the 'conflict mineral' category, while the rest of DRC mines are well-regulated, controlled, and mechanised. Most are situated in the Copperbelt area away from ongoing violence in the East of the DRC [30].

Under the new mining conduct code, the Congolese Government have validated hundreds of mining sites as conflict free (Law. No. 18/001, 2018). In this regard, artisanal and small-scale mining, which provides ~10% of DRC Co production, is currently being regulated by the government [20]. Furthermore, Co supply from artisanal mining, despite associated ethical issues, is essential to reduce risks of supply shortages [31]. Negative perceptions heavily impact local mining revenues, livelihoods, and foreign investment. In addition, global Co supply chain risks are frequently reported, because most mining is taking place in the DRC [32], and this is associated with poor governance, political instability, recurring violence, and financial corruption [33,34].

With respect to Co extraction, land-based mining methods depend on the grade, morphology, structure, depth, shape, dip, subsidence, uniformity, rock substance strength and available technology. Open pit mining is fast and low-cost, and ideal for widely spread low-grade ore bodies located near the surface. However, the time gap between overburden removal and extraction must be short to justify costs [35]. Underground mining is used for higher grade, small or deep ore bodies. Methods used include room and pillar mining for level or shallow dipping deposits, with block caving used for large, uniform deposits [13]. Open pit and underground mining can be integrated simultaneously. The open pit can commence extracting Co ores at surface level whilst the underground workings are constructed. This allows shallow and deep areas of the ore body to be mined to save time [13]. However, current environmental regulations and improvements in mining techniques mostly favour underground mining [36].

Processing of Co-containing ores depends on the deposit type, composition, nature of the final product, market requirements, site location, logistics, labour skills, availability of energy, recovery efficiency and costs [37]. Two major processing pathways exist for producing Co metal. Hydrometallurgy uses differences in solubility and electrochemical properties and involves leaching, followed by concentration, purification (by solvent extraction or ion exchange) and metal recovery (by electrolysis or precipitation). Pyrometallurgy uses variations in melting points and density to chemically remove Co using heat and reducing agents, so that impurities are expelled as gaseous emissions or diverted into a slag, with Co and Ni separated after the smelting step [38]. The types of processes involved in each extraction pathway will vary according to the type of ore deposit and its mineralogy [39].

In the hydrometallurgical method of mining cobalt containing sulphide ores, the ore is often treated by a sulphatising roast in a fluidised bed furnace and the resultant calcine reduced. The Cu-Co ores of DRC and Zambia were historically treated through sulphatising roast into soluble oxides although, recently, mines such as Tenke Fungurume in the DRC use sulphuric acid leaching followed by solvent extraction and electrowinning for copper with cobalt being precipitated as a mixed hydroxide precipitate. With diminishing sulphide ores of nickel, the high-pressure acid leaching (HPAL) process has been developed to treat nickel laterites, mainly the limonitic type ores, many of which contain cobalt [40]. The HPAL method, being the most common process used, is also suitable for ores where acid consumption should be lower [41]. Generally, hydrometallurgical methods consume less energy and generate less emissions, require lower capital costs, and have higher extraction efficiency, however, they produce large quantities of acid waste, involve complex processing steps, and cause higher disposal costs for acidic leachates/wastewater [42].

In pyrometallurgical extraction, as the name suggests, the refining process uses heat to separate the minerals withing the ore. This Co extraction method is energy and $CO_2$ intensive, and emissions rise significantly if coal or oil are used for heating the ore (to separate the metals based on their melting point and density) [20]. This method also results in hazardous gaseous emissions but does not generate wastewater and requires fewer processing steps than hydrometallurgical methods [42]. Although hydrometallurgical extraction of Co is believed to more common that pyrometallurgical extraction, the exact industry share of both technologies could not be accurately estimated due to lack of standardised data.

Following Co extraction, the next step, i.e., refining, involves removing impurities using electrolytic processes, solvent extraction, and electrowinning. Refined Co is manufactured and traded as concentrate, intermediate compounds, high purity metal and salts [13]. Refined cobalt products are traded as metals (powders, granules, briquettes, cathodes, rounds, pellets, ingots), cobalt salts (chlorides, sulphates, nitrates, carbonates, acetates), oxides and carboxylates [43].

## 3. Responsible Co Sourcing

With the DRC providing the majority of globally mined Co, legislative efforts have been made to improve working conditions in conflict-prone regions. The Organisation for Economic Co-operation and Development (OECD) have due diligence requirements that help companies to respect human rights through recommendations for best practices and purchasing decisions. Third-party audits and annual reports maintain responsible supply [44]. The Responsible Minerals Initiative (RMI) helps companies use tools and resources to meet international standards and improve regulatory compliance [45]. The European Battery Alliance uses trade policy instruments to guarantee equal, ethical, and sustainable access to Co [46]. The China Chamber of Commerce of Metals (CCCMC) conducts investment, co-operation, and trade to strengthen responsibility by following United Nations principles [47]. The Responsible Assessment Framework ensures competency of Co producers and buyers when evaluating and reporting on responsible production and sourcing risks, and on responsible working conditions, human rights, child labour, conflict, corruption, air, water, soil, biodiversity, livelihoods, and resettlement [48]. Compliance allows mines and companies to receive export certificates which enhances reputations and meets customer satisfaction and investor expectations.

In the DRC, Entreprise Générale du Cobalt have a trade agreement with Trafigura, working in collaboration with Chemaf, the cooperative COMIAKOL, and the Non-Governmental Organisation PACT, to uphold occupational safety and access control standards [49]. At the Mutoshi mine, artisanal workers use machine prepared vertical shallow pits with relatively higher productivity, greater income, and safety standards. The Sustainable Intelligent Mining Systems (SIMS) project uses drones in dangerous mining locations to reduce inspection times and detect safety concerns [50]. Children and pregnant women are prohibited and access to mines is granted after identification checks at supervised gates. Personal protective equipment, regular onsite training, and bikes for loading ores are provided. Quality control checks are conducted, and ores are marked with unique tracking codes [49].

Major global companies such as Apple also carry out interviews with employees, inspections and publicly discloses process reviews on responsible Co sourcing [51]. Advances in blockchain tracing improves operational efficiencies, minimises fraud and builds confidence by logging the history, location, distribution, and application of each ore with respect to its weight, quantity, and grade. These certificates are shared and validated against previous records as part of statutory compliance [52]. Due to legal provisions to promote local development, prosperity, and growth, Huayou Cobalt locally spends a proportion of their profits on community projects and financing relocation [53].

Based on our review of the existing research, in addition to current practices, several new steps are recommended to ensure more responsible Co sourcing and mining. Employees should have improved education opportunities and helped to uphold responsible mining standards. Although artisanal mining is labour intensive, it should not be omitted from the supply chain. Instead, rules for compliance should ensure its coexistence with large mining operations [54]. Multi-criteria certification schemes that guarantee comprehensiveness, accountability, transparency, and governance should be widely distributed. These must be detailed yet scalable, flexible, and adaptable. All development stages should have routine audits and independent certified approvals by a proportionate commission, including governments and industry representatives [55].

## 4. Alternative Extraction Techniques for Co

Co is found in soils due to organic matter degradation, weathering, and atmospheric deposition of minerals which is influenced by geology, soil age, land use and climate [56,57]. In regions where conventional mining methods have become uneconomical, phytomining can be used, employing hyper-accumulator plants to absorb metals from soils. These are then harvested and combusted to produce an ash containing high metal concentrations. The ash is sintered and smelted before undergoing recovery by acid dissolution to produce a leachate containing dissolved metals which are then obtained by electrowinning or displacement reactions [58]. This has advantages including potential for simultaneous energy recovery. Phyto-mining would allow extraction from low-grade Co resources with reduced waste production. It removes hazardous metals and cleans up contaminated ground [59]. There are no reported examples of phytomining being used to produce Co. There are, however, limitations to the application of phyto-mining including the target metal prices, the plant biomass and the metal yields of the plant [60].

Bioleaching is a Co extraction technique that uses bacteria to extract Co from mine-tailings. Microbes oxidise minerals to separate metal from ore via an enzymatic strike or displacement reaction [60]. It is cost effective, safe, and reduces mining wastes. Bioleaching also avoids harmful emissions, stabilises sulphate toxins and recycles living biomass [61]. Previously identified Co deposits could be exploited using bio-recovery strategies [13], and potentially unconventional Co deposits, including laterites, abandoned mines and volcanogenic massive sulphide (VMS) deposits [15,62]. Generally, bioleaching methods have advantages such as low operating costs, low chemical consumption and toxicity impacts, but high efficiency even at low metal concentrations. However, disadvantages of bioleaching include slow kinetics and longer production times, toxicity impacts to microbial communities, and low solid to liquid ratios [42].

Deep sea mining uses hydraulic pumps or bucket systems to retrieve ocean minerals [63]. The associated environmental impacts include contamination, noise, compaction of the seafloor, destruction of habitats, disruption of fragile ecosystems, formation of sediment plumes and alteration to ocean geochemistry [64,65]. Environmental management techniques, regular impact assessments, and strict monitoring can be applied to mitigate environmental impacts [66]. The use of risers can also prevent mixing of ocean floor seawater and the water column [67]. However, deep sea mining to recover Co is technically difficult, and with world metal prices remaining stable, the economic viability deep-sea mining is not proven [68]. Moreover, factors such as metal recycling, new onshore deposits, and technological limitations have delayed the commercial exploitation of deep-sea mineral deposits [69]. It is estimated that mean metal content in deep-sea Co-containing ores is greater than in terrestrial deposits [70], and this explains why deep-sea mining still attracts significant interest and investment.

Another possible Co extraction technique concerns asteroid mining using small spacecraft to exploit near-earth asteroids containing volatile and high value minerals [71]. However, this method has not been developed and uncertainties regarding its economically feasibility, environmental impacts, and ethics of space-based mining remain unanswered [72].

Most Co is a by-product of Ni or Cu extraction so metallurgical processing is not optimised for Co recovery and smelting is inefficient. The fate of ~40–60% of Co is in tailings and slags [38] and recovering Co from waste piles in the form of landfill mining is challenging. Excavating waste is expensive, valuable metals need sorting, reburial is required, and finding significant quantities is unlikely. Recovery from extractive and industrial wastes is more technologically advanced, easier, and more promising as this waste is more homogenous and better understood. Therefore, we recommend different recycling methods for Co are assessed at an industrial scale in the future based on cost, environmental impact and energy requirements.

## 5. Developing a Circular Economy for Co

A circular economy ensures resources remain in the economy for as long as possible, mitigating both virgin resource extraction and end-of-life disposal. It also reduces production wastes, emissions, and wastewater, and prolongs the lifetime of materials and products, helping to build long-term resilience and sustainability [73].

Co is an energy-transition metal that is expected to undergo severe market competition due to the increase in low-carbon technology development [74] and limited mining reserves. For these reasons, improvements, to diversify both primary and secondary supply, to reduce disruptions and increase resilience, are essential [34]. Increased secondary supply through a circular economy will help achieve SDGs and key environmental targets, including the transition to net zero. A circular economy for Co offers particularly advantages in the transportation and electric mobility sectors.

To facilitate a net zero transition and achieve the Paris Agreement target of reducing global mean temperature rise to well below 2 °C (compared to pre-industrial levels), annual EV sales must account for at least 35% of global vehicle sales by 2030. This is estimated to require 1.2 million tonnes of Co [75]. Moreover, EV batteries need to be safe and long lasting [76], with used battery collection rates required to increase to least 70% by 2030. Current recycling rates are low, at about 32%, and much less than what is economically possible and what is needed to meet projected Co supply shortfalls [77].

An important factor impeding the expansion of this sector is the lack of standardisation, making recycling processes complex (wide range of battery types, different chemistries, and forms) and thus expensive. Perhaps the very efficient recycling of up to 98% for lead-acid batteries could offer key insights to improve spent EV battery collection, transport, processing, and recycling.

From a recycling and resource recovery perspective, future focus needs to be on post-consumer EV batteries, though this should be in coordination with improved battery performance and longevity at the design/production stage. For secondary Co, spent rechargeable batteries and scrap, Co-containing alloys could be the main pivots of a circular economy. Current projections show that the global EV recycling industry is expected to triple by 2060 [77], with Europe having ~10% Co from previously consumed batteries [19]. A circular economy via enhanced recycling also allows shorter supply chains located closer to end users, reducing transport/shipping costs and pollution [78].

Price fluctuations are critical because if the value of primary Co increases, secondary Co becomes more financially attractive. Moreover, the presence of supplementary metals in Co-containing scrap affects the overall economic feasibility of recycling [79]. Perceptions around recycled materials affects the circular economy transition for Co, as recycled materials are perceived to have inferior quality, efficiency, and/or safety. Research and testing into Co recovery from used batteries should be communicated to various stakeholders to improve transparency [80]. In this regard, collection services, battery testers, recycling companies and manufactures should create a single, straightforward, and effortless destination point for users [81]. The standardisation of Co-containing EV batteries could make the recycling systems more accessible and efficient, making Co recycling systems economically feasible, environmentally sustainable, and technologically advanced, thus enabling a robust circular economy for secondary Co [82].

With respect to secondary Co extraction, recycling of Co-containing batteries is the most feasible method. This uses a mix of mechanical, pyrometallurgical and hydrometallurgical processes. Mechanical methods break batteries apart by crushing and grinding, to concentrate metals and remove electrolytes. However, the quality of cathode materials salvaged does not always meet standards [83]. Pyrometallurgy involves processing materials in a smelter, without mechanical pre-treatment, with Co recovered as an alloy. This is flexible for different inputs and is capable of handling large volumes but has a high energy consumption and needs additional refining steps and treatment of gaseous emissions [84]. Hydrometallurgy requires mechanical pre-treatment to remove organics which would otherwise interfere with solid–liquid separation, with Co recovered using acid leaching followed by precipitation [84].

Spent batteries, classified as scrap, are a major potential source of secondary Co. They will differ in Co composition but will usually contain concentrations of 5–33% [85]. Recovered Co from spent products can come from new and old scrap. New scrap originates from processing and manufacturing residues, during shaping, cutting, and moulding. Old scrap is from end-of-life products, such as spent batteries, old turbine blades, jet engine parts, cemented carbide cutting tools, magnets and used catalysts. New scrap does not require pre-treatment and can be re-melted directly, whereas old scrap must be quantitatively measured and categorized before being recycled in existing large smelters with primary Co.

Scrap is melted under reducing conditions, followed by refining and casting. This method allows large quantities to be processed. Other metals that co-exist in Co alloys can also be economically recovered. Small amounts of Co are easily oxidised during smelting, but most can be retrieved by slag cleaning [86].

For post-consumer used EV batteries, current regulations are still unclear and do not enforce extended producer responsibility. There is an incentive for primary battery producers as remanufactured batteries can provide adequate performance suitable for less-strenuous applications such as stationary energy-storage and off-grid renewable energy storage [87]. However, reuse and remanufacturing sectors face several obstacles. First, batteries lack a standardised design or chemistry, thus making refurbishing or remanufacturing complex. Second, as new batteries become economically competitive, the price gap between new and old will decline, making remanufacturing less economically attractive even when appropriate technology exists. At present, a reconditioned battery saves 30–70% in costs. However, with savings dropping significantly in the future, the viability may become questionable. Thus, modernising, developing, and expanding the scale of remanufacturing processes will ensure sufficient savings are accrued to justify remanufacturing of EV batteries.

## 6. Conclusions

Co is technologically important because $LiCoO_2$ and its derivatives are used as the positive electrode in lithium-ion batteries. These are used in electric vehicles and demand for Co is expected to increase by a factor of ~20 by 2050. Most Co is produced as a by-product from Cu and Ni production with ores extracted from both large mines and artisanal mines, mostly in the DRC. Current mining practices are considered unsustainable and unlikely to meet the growing market for Co. Alternative sources such as deep-sea mining are unlikely to be viable and are associated with significant environmental issues. Secondary supply and the recycling rates of Co are low, but with huge potential to be increased and optimised. It is therefore critical that there is renewed focus on developing a circular economy for Co, in which the current linear model of resource extraction, use and disposal is replaced by one in which Co is extracted at end of first life, so that it can remain in the economic cycle for as long as possible. There are issues with the complexity of Co recycling due to lack of standardisation of design and chemistry, particularly in lithium-ion batteries. However, this is the only way that existing technologies that rely on Co will be able to contribute to a sustainable future.

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