Battaia, O. and Oloruntoba, R. and Guillaume, R. 2024. Preventing Adverse Environmental And Social Outcomes In Sustainable Value Chains In Nickel Extraction And Refining. In: 6th Conference on Production Systems and Logistics, 9-12 Jul 2024, Honolulu Hawaii USA.

CPSL

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2024

6th Conference on Production Systems and Logistics

Preventing Adverse Environmental And Social Outcomes In Sustainable Value Chains In Nickel Extraction And Refining

Olga Battaia[1], Richard Oloruntoba[2], Romain Guillaume[3]

[1]*Kedge Business School, Bordeaux, France*
[2]*School of Management & Marketing, Faculty of Business and Law, Curtin University, Bentley, Australia*
[3]*Université de Toulouse, IRIT, Toulouse, France*

Abstract

This paper investigates and analyses sustainable value chains in the nickel production. Nickel is crucial for the global transition to renewable energy sources as battery-grade nickel contributes to the development and scalability of the electric vehicle (EV) industry. At the same time, the nickel industry faces several significant environmental and social challenges, such as inefficiency in resource use including overconsumption of energy and water, and minimal community engagement. These challenges must be urgently addressed to achieve sustainable solutions, particularly as the EV industry and other battery users grow to meet global demand. In this paper, we investigate solutions for mitigating adverse environmental and social impacts through a systematic literature review.

Keywords

Sustainable supply chains; sustainability; ore mining; Nickel extraction and refining; responsible production and consumption

1. Introduction

Nickel, a versatile and indispensable metal, plays a critical role in various industries, ranging from aerospace to electronics, and its importance continues to grow with the rise of electric vehicles and renewable energy technologies [1]. However, the extraction and refining of nickel present significant environmental and social challenges that cannot be overlooked [2]. As concerns about climate change, environmental degradation, and social equity intensify, there is increasing pressure on industries to adopt sustainable practices throughout their value chains. In the case of nickel extraction and refining, this entails not only minimizing the environmental footprint of operations but also ensuring the well-being of local communities, safeguarding biodiversity, and upholding the rights of workers. This article aims to explore the complex landscape of sustainable value chains related to the nickel exploitation with a particular focus on the extraction and refining operations.

Estimates of nickel resources vary due to the incompleteness of industrial mining activity data as some key supplier countries have low rates and standards of disclosure. According to U.S. National Minerals Information Center (2024), globally, nickel resources have been estimated to contain more than 350 million tons of nickel, with 60% in laterites (e.g. Philippines, Indonesia, Brazil, Colombia) and 40% in sulphide deposits (e.g. Russia, Canada, Australia). The methods employed to produce metallic nickel vary depending on the type of ore. Sulfidic ores are accessible through both open-pit and underground mining methods, while oxidic ores are exclusively mined through open-pit operations.

DOI:
ISSN: 2701-6277

publish-Ing.

Historically, sulfidic ores served as the primary source of nickel, as oxidic ores are costlier and involve more intricate processing [2]. However, in recent years, nickel production from oxidic ores has substantially increased driven by rising demand, the presence of more abundant oxidic ore reserves, declining sulfidic ore grades, and advancements in leaching technologies [3]. Two categories of nickel are recognized: class I nickel, boasting a nickel content of 99% or more, primarily used for battery and catalyst applications, and ferronickel, which serves as the main form of nickel consumed in alloy production. Given that nickel is often found alongside other metals in ores, substantial quantities of ferronickel are annually produced from oxidic ores, while the extraction of nickel from sulfidic ores also yields copper, cobalt, and platinum group metals, albeit in descending proportions [4].

The majority of nickel sourced from laterite deposits is currently channeled towards stainless steel production [2]. In contrast, nickel extracted from sulfide deposits finds diverse applications across various sectors, notably as a cathode material for lithium-ion batteries (LIBs) [5]. Its integration contributes to cost reduction in battery manufacturing due to its relatively lower price compared to alternative materials like cobalt [6]. LIBs are extensively employed in electric vehicles due to their superior energy density, absence of memory effect, and minimal self-discharge [7].

Nickel is acknowledged as a crucial metal in the realm of low-carbon technologies [8]. As society strives towards achieving net zero emissions through the widespread adoption of such technologies, the demand for metals like nickel has seen a substantial rise to feed the energy transition [9]. The lithium-ion battery is poised to assume a pivotal position in the effort to decarbonize transportation and grid-scale energy storage, presenting an ethical conundrum. Meeting ambitious goals for decarbonization and electrification necessitates an increase, rather than a decrease, in the demand for raw materials for batteries [10,11]. Moreover, the energy needed to produce these materials is likely to come from fossil fuels, potentially impeding the reduction of carbon intensity in industry [12] even if efforts are made to integrate renewable energy technologies into mining operations [13]. Innovations throughout the supply chain emerge as the sole feasible approach to accomplish widespread decarbonization at scale. In order to critically assess the existing research in the field, we perform a systematic literature review. The methodology adopted is presented in next section.

2. Literature analysis

2.1Literature search method

The secondary research was performed on Google Scholar limited to documents written in English. The following keywords were used: “Sustainable value chain” OR “Sustainable supply chain” AND (“Nickel extract*” OR “Nickel produc*” OR “Nickel refin*” (“Nickel” AND (“Mineral” OR “Mining”) AND (“extract*” OR “produc*” OR “refin*”). In total 1050 articles were retrieved, they were sorted on the basis of abstract resulting in 347 distinct papers which were considered relevant during the preselection phase. These articles were read full-text, and a snowball search has been realized both within cited and citing articles. The page limitation does not allow to discuss all of them and in the current analysis 120 the most relevant articles were selected to support the main insights from the literature review. The retrieved articles can be roughly classified in 5 main categories discussed in Subsections 2.2-2.4 and further in Sections 3-4:

- Assessment of environmental impacts, circularity and recycling of nickel products (subsection 2.2)
- Strategies to secure the resilient supply chain for critical raw materials and establishment of new mining and mineral policies
- Alternative (more sustainable) processes for mineral processing industries (subsection 2.4)
- Environmental impacts of nickel production (Section 4)
- Social impacts of nickel production (Section 5)

2.2 Assessment of environmental impacts, circularity and recycling of nickel products [14]-[37]

The environmental impacts of nickel products and in particular of lithium-ion batteries have garnered significant attention due to their crucial role in powering various technologies, including electric vehicles and renewable energy storage systems. Life Cycle Assessment (LCA) studies have provided valuable insights into the lifecycle environmental footprint of these batteries, highlighting key areas of concern such as greenhouse gas emissions and resource utilization. However, the complexity of the lithium-ion battery value chain presents challenges in accurately assessing and mitigating these impacts. Factors such as variability in battery composition, design, and manufacturing processes contribute to a wide spectrum of reported values for carbon footprint and other environmental indicators. Nevertheless, consensus appears to converge on the primary sources of significant impacts: the production of cathode active materials (such as nickel) and the manufacturing of battery cells.

Although methodologies and tools for conducting LCAs, whether in general for batteries or specific to nickel production, are readily accessible, there persists an urgent requirement for enhanced and up-to-date primary data at an industrial scale. Data gaps and uncertainties in LCA studies can lead to inaccurate assessments of environmental impacts and hinder the development of effective mitigation strategies. In particular, the co-production of different metals from the same mine makes difficult the allocation of impact to individual minerals. Also, the predominant focus in evaluating the environmental impacts of batteries has revolved around greenhouse gas (GHG) emissions. To achieve a more comprehensive understanding of battery sustainability, it is crucial to incorporate a more diverse range of indicators discussed here below. To address this challenge, collaborative efforts between industry, academia, and government agencies are needed to collect, analyze, and share data on mining activities, manufacturing processes, supply chain logistics, and end-of-life management practices. By enhancing data transparency and accessibility, stakeholders can make better informed decisions to promote the sustainable development of the global mining industry and associated manufacturing.

One hurdle involves assessing the complete lifecycle of batteries encompassing their end-of-use considerations. Statistics vary across different references, but as reported by the U.S. National Minerals Information Center (2024), recycled nickel in various forms represented roughly 57% of apparent consumption in 2023. However, the majority of reclaimed nickel is typically recycled in alloy form, primarily utilized in the production of stainless steel, steel, and other alloys, with secondary production being less common for class I nickel. Attaining fully circular electric vehicle batteries remains a distant aspiration. In the foreseeable future, the primary emphasis will be on producing the required stock of EV batteries for a sizable fleet, primarily relying on new materials. Closed-loop recycling is poised to gain significance progressively, contingent upon factors like the scale of the EV fleet, advancements in battery chemistry, exploration of second-use possibilities, and other variables such as standardization, regulatory frameworks, business models, eco-design principles, collection infrastructure, and recycling technologies. The pivotal factor distinguishing recycling methods is not so much the efficacy of recycling individual materials but rather the retrieval of materials in terms of their chemical composition and purity.

2.3 Strategies to secure the resilient supply chain for critical raw materials and establishment of new mining and mineral policies [38]-[49]

The surge in demand in metals like nickel has spurred governments into action to stabilize their supply chain. Measures such as the Basic Plan for Raw Material Resources Development in South Korea, the Energy Act of 2020 in the United States, the Critical Raw Material Act in Europe, and the New International Resources Strategy in Japan have been implemented for this purpose. Historically, assessments of potential risks in the mining sector have focused on factors such as the geographical distribution of resources, geopolitical considerations, political stability, security concerns, and regulatory frameworks within jurisdictions. Additionally, geological connections, especially when multiple metals are present in the same orebody, have been evaluated as potential risk factors. However, there is now a growing recognition of environmental and social risks, leading to the emergence of a new category of risks associated with obtaining social acceptance to operate. Consequently, the assessment of risk sources has shifted from relying solely on national-level resource estimates to incorporating regional and mine site-level data, taking into account the specific environmental, social, and governance (ESG) risk dynamics surrounding mining projects at the local level.

Studies on Mineral and Mining policies seek to advance transparent and ethical governance of mineral streams in alignment with sustainable development goals. They provide insights into the environmental and social impacts of the mining industry, offering examples from the nickel industry. A number of studies concern the framework established by the United Nations (UN) Convention on the Law of the Sea. Currently, the International Seabed Authority is in the process of formulating regulations concerning the extraction of minerals from the ocean floor, presenting a distinctive opportunity to proactively establish science-based environmental safeguards for mineral extraction. Minerals such as cobalt and nickel show promising potential in oceanic areas, including the continental shelf within states' exclusive economic zones and outer continental shelf regions. In international waters, significant deposits of metals vital for green technologies are found in metallic nodules, as well as cobalt and tellurium crusts situated on seamounts worldwide. Challenges in extraction and diminishing reserves of certain terrestrial minerals, coupled with societal resistance to land-based mining, may increasingly position oceanic mineral reserves as viable alternatives. This underscores the importance of developing strategies that balance the extraction of oceanic minerals with the conservation of these delicate marine environments.

2.4 Alternative (more sustainable) processes for mineral processing industries [50]- [65]

Recent advancements in mineral biotechnology have led to the development of environmentally friendly microbial flotation processes for mineral beneficiation. Numerous studies have explored the potential of microbes and microbial metabolites as flotation reagents for separating gangue materials from valuable minerals. Scientific literature on microbial flotation processes indicates that interactions between minerals and certain bacteria, as well as microbial metabolites, significantly influence their surface properties. While microbial flotation studies have predominantly been conducted on a laboratory scale thus far, there is significant potential to expand this eco-friendly process for use in mineral processing industries. Microbial leaching of low-grade ores offers several advantages over conventional methods, including its relative simplicity, mild operating conditions, low capital costs, minimal energy input, modest labor requirements, and environmental friendliness.

Another alternative is represented by phyto-mining. Such elements, as Ni, Co, and Au, may offer sufficient economic value in phyto-mining biomass of metal hyperaccumulator plants to justify commercial practice. The successful development of phyto-mining entails several key steps, including the selection of high-biomass hyperaccumulator plant species, evaluation of genetic diversity, breeding of improved strains for higher element yields, optimization of agronomic practices, and the development of methods for element recovery from plant biomass. Various plant species and phyto-mining methods for extracting soil Ni have been demonstrated across different climates, including temperate and tropical regions. Commercial phytomining of Ni has commenced in Albania using *Alyssum murale*, while significant trials are underway in Malaysia utilizing *Phyllanthus securinegioides*. However, fluctuating commodity metal prices present challenges to the commercial development of phyto-mining.

The environmental and social impacts of conventional processes in nickel extraction, refinement and production are respectively discussed in Sections 3 and 4.

3. Environmental impacts of nickel production

Academic literature has extensively outlined the considerable environmental consequences associated with the extraction and refining processes of nickel, which encompass habitat degradation, air and water contamination, as well as the release of greenhouse gases. Moreover, studies underscore the necessity of adopting cleaner production methods, enhancing waste management strategies, and bolstering energy efficiency initiatives to mitigate the environmental toll of nickel production [66].

3.1 Habitat Destruction [67]-[69]

Nickel mining operations often entail extensive land clearing and excavation activities, resulting in the degradation of natural habitats such as forests, wetlands, and areas rich in biodiversity, since 40% of global nickel reserves are in locations with high biodiversity and protected areas. This habitat destruction can lead to enduring ecological ramifications, including the displacement of wildlife species, disruption of ecosystem functions, and a decline in biodiversity.

However, relying on biodiversity offsets to counterbalance habitat loss requires a high level of assurance regarding their ecological integrity, especially when they are used to justify the destruction of valuable habitats or rare species. Given the complexity of this concept and the importance of ensuring scientific accuracy, it is not surprising that biodiversity offsetting has faced criticism on several fronts. These concerns encompass the absence of clear guidelines for biodiversity accounting frameworks, the lack of evidence regarding their actual effectiveness, inadequate governance support to prevent offsets from undermining essential steps in the mitigation hierarchy, and the need to fully consider associated risks. Consequently, addressing critical factors such as risk, effectiveness, and the permanence of biodiversity gains within a biodiversity accounting framework remains a significant challenge. Without properly incorporating these parameters, accurately measuring the "no-net-loss" principle becomes challenging.

3.2 Water Pollution [70]-[78]

The extraction and processing of nickel ores can result in the release of toxic substances such as heavy metals, sulphides, and acids into nearby water bodies. This pollution can contaminate surface water and groundwater, posing risks to aquatic ecosystems and human health. Acid mine drainage, a common consequence of sulphide mining, can lower pH levels in waterways, degrade water quality, and harm aquatic life. Acidification of water in water bodies increases the concentration of heavy metal ions in ground and surface waters, leads to the death of fish, amphibian and plant populations, and also makes water undrinkable. Solvent extraction stands out as one of the most efficient methods for removing and recovering nickel from Ni-plating wastewater. However, conventional extraction processes employing acidic extractants often result in the generation of secondary pollutants, such as acidic wastewater.

In efforts to mitigate both initial and secondary pollution stemming from Ni-plating wastewater treatment, a novel acid-free and alkali-free extraction process for nickel utilizing a cleaner extractant known as PEPD has been proposed. This novel approach seeks to address the environmental concerns associated with traditional extraction methods by utilizing PEPD, which offers several advantages, including pollution reduction and enhanced resource utilization efficiency. This approach offers promise for the recovery of nickel from plating wastewater through solvent extraction, providing a method that is both environmentally favorable and conducive to precise operational control. The development of a clean and sustainable process devoid of acid and alkali usage represents a significant step forward in environmental protection and resource conservation efforts.

In order to reduce the water consumption in mining activities, there is an increase in the adoption of water-conservation technologies and practices within the industry such as amongst these innovations, closed-loop water systems (Molchanov & Laplante, 2020). Furthermore, the implementation of real-time monitoring systems allows for precise management of water usage, resulting in reduced consumption and a lower risk of accidental discharges into local water bodies (Brown et al., 2017). These endeavors suggest that despite the multifaceted challenges, solutions that blend economic viability with environmental responsibility are attainable.

3.3Air Pollution and Greenhouse Gas Emissions [79]-[84]

Nickel mining and refining activities are associated with the emission of various pollutants into the atmosphere, including sulfur dioxide, hydrogen sulphide, carbon oxides, nitrogen oxides, metal dust, and benzopyrene. Sulfur and its compounds are among the primary air pollutants emitted during these processes. Approximately 45-55% of sulfur is removed with slag from metallurgical units, while the remainder is released into the atmosphere. Substantial amounts of sulfur dioxide or hydrogen sulphide are emitted during the cooling and processing of slag. Upon entering the atmosphere, sulfur and its compounds undergo transformation into sulfuric acid. When deposited through precipitation, sulfuric acid contributes to environmental pollution and disrupts ecological balance. The increased acidity of soils and water bodies, along with elevated concentrations of metals, inhibit the absorption of water and nutrients by plants, leading to vegetation loss over extensive areas and the formation of industrial wastelands near production facilities.

To address these significant impacts, cleaner alternatives are essential for the long-term sustainability of the industry. Technologies aimed at reducing emissions, such as flue-gas desulfurization and selective catalytic reduction as well as carbon capture and storage are being integrated into modern facilities to mitigate SO2 and NOx emissions. These investments are becoming increasingly economically justified as regulatory bodies heighten scrutiny, and investors grow cautious of environmental risks.

According to some estimations, the emission intensity of greenhouse gases from class 1 nickel production (derived from sulphide ore) exceeds that of refined copper and zinc production by more than twice (IEA, 2021) and contribute to global climate change, exacerbating environmental challenges such as rising temperatures, sea level rise, and extreme weather events. Reducing energy consumption in nickel extraction and refining operations is paramount for mitigating environmental impacts, reducing operational costs, and fostering sustainability. To evaluate energy consumption and greenhouse gas emissions, the developed process models encompass the following four components: (i) mining, (ii) pre-processing (including beneficiation, drying, calcination, sulfidation, sintering), (iii) smelting, and (iv) post-processing (involving settling, converting, refining, roasting). Despite significant advancements in energy management within the mining sector, widespread adoption of best practices has not yet been achieved, as these are still in the process of being implemented. The barriers and motivations for implementing these initiatives can be classified into behavioural, financial, and organizational categories.

3.4 Soil Contamination [85]-[99]

Nickel mining activities can lead to soil erosion, sedimentation, and contamination with heavy metals and other pollutants. Quantification of terrestrial acidification is still understudied (Rachid et al., 2023). Terrestrial acidification is a consequence of acid mine drainage. Highly acidic waters can solubilise heavy metals and other toxic elements. Through rain and groundwater, these toxic and acidic streams spread through the environment, acidifying and contaminating the soils of terrestrial ecosystems. Contaminated soils may pose risks to human health, agricultural productivity, and ecosystem integrity. Additionally, the spread of mining waste and tailings can degrade soil quality, reduce fertility, and impair the ability of ecosystems to support plant and animal life.

The assessment of heavy metal pollution and the local phytoremediation potential of contaminated sites is an important prerequisite for phytoremediation. Several species such as spinach, ricinus, cabbage, bean, sorghum, barley, and tomato have been tested and showed a progressively decreasing efficiency in the removal of nickel.

4. Social impact of nickel production

Scholars have also examined the social dimensions of sustainability in the nickel value chain, several factors addressed are discussed here below.

4.1 Health Hazards [100]- [104]

Despite its widespread commercial use, e.g., in coins, stainless steel cooking utensils or taps, nickel salts and oxides are classified as class 1 carcinogen, while metallic nickel and its alloys as possibly cancerogenic (group 2B) by IARC. Toxic effects of Ni on immune and respiratory system are closely linked to occupational inhalation from fossil fuel combustion or nickel-related manufacturing. This route affects most often metal refineries or plating industry workers, although people inhabiting areas in proximity of nickel mining, processing and recycling sites are also endangered. Molecular mechanisms of nickel toxicity, despite not fully understood, also connect to oxidative stress and mitochondrial dysfunction, resulting in numerous mental disorders.

4.2 Economic impact on well-being [105]- [108]

The Human Development Index serves as a crucial measure for gauging human well-being, encapsulating factors like life expectancy, education, and income per capita. However, within the mining sector, particularly in the extraction of critical minerals such as lithium, nickel, gold, cobalt, and copper, the well-being of the workforce often takes a back seat. Despite this, the mining industry, especially in resource-rich nations, plays a pivotal role in bolstering economic stability, contributing significantly to GDP. This economic impact extends beyond extraction alone, influencing ancillary services like logistics and maintenance, thereby enhancing employment opportunities and overall economic health. Miners also typically benefit from higher-than-average wages and additional perks, leading to an elevated standard of living. Nevertheless, this prosperity can be tenuous due to the volatile nature of global commodity prices, potentially resulting in workforce reductions or operational changes.

Yet, within this economic framework, challenges persist, particularly regarding wage disparities along gender lines. Men tend to earn 15-20% more than their female counterparts, contributing to an imbalanced earning structure and dissuading women from entering the sector. These disparities have broader implications, affecting metrics like Gross National Income (GNI) per capita, educational achievements, and health outcomes. Moreover, the mining industry is fraught with occupational hazards, including exposure to hazardous chemicals and long-term health conditions, alongside mental health challenges stemming from extended periods of separation from families. The sector's cyclical nature and the increasing adoption of automation technologies further exacerbate concerns about job security.

4.3 Labor Exploitation and discrimination [109]- [111]

The mining sector is a cornerstone of global economies, directly employing over 40 million people and making significant contributions to national GDPs, particularly in developing countries. The workforce demographics and gender dynamics within this sector play pivotal roles. Literature shows that a more balanced and diverse workforce positively impacts well-being indicators such as health, education, and living standards within mining communities. Recognizing the importance of workforce diversity and gender representation is not just a moral consideration but also an economic and social imperative for the sustainable development of mining regions.

However, the distribution of the mining workforce, frequently located in rural areas due to the geographical placement of mineral deposits, presents unique challenges for infrastructure, housing, and regional economic development. This distribution encompasses a wide array of roles and specializations, contributing to a discernible urban-rural divide within mining communities. Historically, the mining industry has been male-dominated, with cultural, economic, and policy-driven factors marginalizing women. While technological advancements have expanded skill requirements to include fields traditionally associated with women, such as geology and management, barriers persist, including biases and lack of mentorship opportunities. Despite these challenges, there has been a gradual increase in female representation in the mining workforce, driven in part by initiatives from organizations like Women in Mining (WIM) and International Women in Mining

(IWiM), as well as corporate policies promoting gender equality. Major corporations have also implemented inclusive policies and flexible work arrangements to foster a more gender-inclusive culture.

Women in the mining sector face numerous challenges, including safety concerns, systemic discrimination, and cultural norms that perpetuate gender disparities. Efforts to address these challenges include capacity-building programs, awareness campaigns, and legislative measures such as quotas to ensure a minimum percentage of female workers. Despite progress, fostering true gender equality in the mining industry requires ongoing commitment from stakeholders at all levels to dismantle systemic barriers and create a more inclusive and equitable environment.

4.4 Displacement of communities and conflicts over land rights [112]- [117]

Nickel mining projects often require large tracts of land, leading to the displacement of communities living in or near mining areas. Forced resettlement can disrupt traditional livelihoods, social networks, and cultural practices, leading to social dislocation, loss of identity, and psychological stress among affected populations. The acquisition of land for nickel mining projects can give rise to conflicts over land rights, particularly in areas where indigenous peoples or marginalized communities have customary land tenure. Disputes over land ownership, access, and compensation can escalate into social unrest, protests, and even violence, exacerbating tensions between mining companies, governments, and local communities. The literature shows the growing importance of social acceptance to operate taking into account the specific environmental, social, and governance dynamics surrounding mining projects at the local level.

4.5 Education and Skills Development [118]- [120]

The mining industry faces significant challenges in attracting a skilled workforce. Called "war for talent", this challenge can jeopardize the competitiveness of mining products in developed countries, with implications for national security and the availability of critical materials for modern technologies. Initiatives are implemented to revitalize the industry by preparing future mining leaders through interdisciplinary education focusing on technological innovation, environmental stewardship, and social responsibility. A comprehensive rebranding effort is needed to attract youth interested in blending economic rewards with positive global impact. To facilitate the transformation of the mining industry, significant changes are needed in marketing and communication strategies to portray mining as a cutting-edge, socially responsible field that appeals to today's youth. Universities, community colleges, government agencies, and industry associations must collaborate to elevate the industry's profile and highlight the diverse job opportunities it offers. Transparency in environmental, social, and governance practices is crucial to building credibility and trust among prospective students and the wider public.

5. Concluding remarks

The systematic literature analysis shows that there's a growing emphasis on sustainable practices within the mining sector in general and in nickel industry in particular, aiming to bolster economic contributions while ensuring consistent workforce security and minimizing the environmental and social impacts. This shift towards sustainability, signals positive trends for industry alignment with sustainable development goals. Nonetheless, navigating the complexities of sustainability in mining remains a daunting task, necessitating ongoing efforts to address disparities, mitigate environmental and social risks, and promote well-being within the workforce and local communities. To address the existing challenges, collaborative efforts between industry, academia, and government agencies are needed to work on the existing behavioural, financial, and organizational barriers for the global implementation of more sustainable mining practices across the world.

Acknowledgements

This research was partially supported by Academy International Programs of Australia-France Social Science Collaborative Research Program and France Embassy in Australia. The authors thank Médéric Suon for enriching discussions that nourished the content of the article.

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Biography

Olga Battaïa has been Associate Dean for Research at Kedge Business School since 2000. Prof. Dr.-Ing. habil. Olga Battaïa serves as Associated Editor for the Journal of Manufacturing Systems, IISE Transactions and Omega-the International Journal of Management Science. She is also a Member of IFAC Technical Committee 5.2. Management and Control in Manufacturing and Logistics.

Richard Oloruntoba is Associate Professor of Supply Chain Management (SCM), Curtin Business School, Curtin University, Australia since 2020. He has worked 22 years as a SCM researcher and educator in UK and Australian universities. He is Associate Editor of Journal of Responsible Production and Consumption, and UNSDG Advisor for Emerald Publishers UK for Australia/NZ.

Romain Guillaume is MCF HDR in the fields of operational research and artificial intelligence. His research focuses on optimization and decision-making under uncertainty. His applications focus on managing uncertainty in the supply chain.