Materials Circular Economy (2024) 6:51
https://doi.org/10.1007/s42824-024-00146-5

ORIGINAL PAPER

Enhancing ESG Practices in Lithium Battery Recycling: A Review of Current Policies and Proposed Solutions

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Received: 19 July 2024 / Revised: 2 August 2024 / Accepted: 13 August 2024

Abstract

Lithium batteries, essential for various technologies, have a recycling rate of only 1%, significantly lower than the 99% rate of lead-acid batteries and falling short of the UN's Sustainable Development Goals. Current Environmental, Social, and Governance (ESG) policies are flawed, with CEOs prioritizing lithium mining over recycling, disrupting the circular economy, and often being unaware of ESG's impact on stock prices and financial risks. The low recycling rate of lithium batteries poses a significant challenge to sustainability. The ESG rating system, which measures corporate practices in environmental, social, and governance areas, is crucial to stakeholders but currently inadequate in addressing the recycling issue. The prioritization of mining over recycling by CEOs further exacerbates the problem, highlighting a lack of awareness about the financial and stock price implications of poor ESG practices. Solutions are as follows: Battery passport, implementing a battery passport system to track the lifecycle of Lithium batteries and ensure proper recycling; federal funding, allocating federal funds to support recycling initiatives and infrastructure development; global CO2 emissions tax, introducing a global CO2 emissions tax to incentivize better ESG practices for lithium batteries; and Google Trends data, utilizing Google Trends data from 2004 to 2023 to validate and refine these solutions, ensuring they are aligned with public interest and awareness. These solutions aim to enhance ESG practices for Lithium batteries, promote recycling, and support the circular economy.

Keywords Environmental, Social, and Governance (ESG) · Sustainable Development Goals (SDGs) · Lithium batteries · Circular economy · Recycle

Abbreviations

SDGs	The Sustainable Development Goals
ESG	Environmental, Social and Governance
CEO	Chief Executive Officer

Highlights

- The recycling rate of Lithium batteries is 1% versus 99% for lead-acid batteries.
- Cost-oriented CEOs mining lithium cheaper than recycling disrupt circular economy.
- Many CEOs are not aware of the importance of ESG on stock prices and financial risks.
- Battery passport, federal fundings, and global tax on CO2 emissions may improve ESG.

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Introduction

Lithium batteries, which are extensively utilized in a variety of devices such as mobile phones, electric cars, and grid and utility systems, have a recycling rate of just 1% (Zhao et al. 2024). This is significantly lower than the 99% recycling rate of lead-acid batteries (Makwarimba et al. 2022) and falls short of the global targets established by the United Nations' Sustainable Development Goals (SDGs).

Ramasubramanian et al. (2024) reported that lithium-ion batteries help reduce greenhouse gas emissions and combat the climate crisis. They aimed to improve their performance and sustainability or develop new battery chemistry. However, their production, use, and disposal are waste-intensive. Greater circularity would make them more sustainable. They discussed sustainability and circularity principles for secondary batteries, considering the life cycle of lithium-ion batteries, material recovery, component reuse, recycling efficiency, environmental impact, and economic viability. Addressing these issues through research and development can enhance battery sustainability, safety, and efficiency,

Published online: 19 August 2024

supporting stable grid-scale operations and safe electric vehicle use, including end-of-life management and second-life applications.

Li et al. (2024) presented that recycling and reusing spent lithium-ion batteries help address resource scarcity and environmental pollution. Despite progress, challenges remain in efficiency, effectiveness, and sustainability. Their review analyzed the current status of battery recycling, comparing different processes and introducing emerging techniques like deep eutectic solvents, molten salt roasting, and direct regeneration. They also suggested upgrading recycled materials into high-value functional materials, such as catalysts and graphene. Their review explored the economic and environmental impacts of recycling and highlighted the need for future technologies to balance efficiency, economics, and environmental benefits. Policy recommendations were proposed to promote sustainable battery development (Li et al. 2024).

Bird et al. (2022) addressed that lithium-ion batteries are widely used in consumer products and electric/hybrid vehicles. Due to limited sources of battery components and increased demand, recycling is essential to mitigate environmental and material costs. Recycling costs depend on newer methods, effective use of capacity, and local development. While battery recycling benefits manufacturers, consumers, and recyclers, many benefits are not monetizable. Regulations are likely needed to realize these benefits and preserve society and the environment. They discussed global battery recycling regulations, focusing on the USA, EU, and China, and their market impacts (Bird et al. 2022).

This study explores the factors contributing to the low recycling rate of lithium batteries. A comprehensive literature review was undertaken, focusing specifically on the underwhelming recycling rate of these batteries. The findings from the review indicate that the cost of extracting lithium from natural resources (Tabelin et al. 2021) is significantly lower than the expense associated with recycling the same material from spent batteries (Garcia et al. 2023). It is crucial to address this issue of low lithium battery recycling rates to achieve the SDGs. Failure to do so could potentially lead to a decline in the stock value of companies involved in the lithium materials industry.

The scope of this paper is to examine the current issues of lithium batteries on environmental, social, and governance (ESG) and the impact of ESG on stock prices from a sustainable perspective of the United Nations' Sustainable Development Goals (SDGs). This paper will present potential solutions to the current ESG problem regarding the Lithium battery issue.

In their exhaustive review, Zanoletti et al. (2024) delved into the multifaceted world of lithium-ion battery recycling. They explored a broad spectrum of topics, from the state-of-the-art recycling technologies and recent advancements to the existing policy gaps and strategic design approaches. Their review also addressed the financial aspects, discussing the funding allocated for pilot projects, and presents an all-encompassing strategy for battery recycling. They underscored the hurdles in the path of developing LIB recycling, while simultaneously highlighting the silver lining—the potential for innovation and the prospect of fostering a more sustainable, circular economy. This dual perspective presented challenges as opportunities, paving the way for future advancements in this field.

Google Trends, a robust tool, is utilized in this study to analyze the relative popularity trends of multiple key terms or phrases. These relative comparisons are used to substantiate the proposed hypotheses. Google Trends serves as a valuable resource for procuring datasets and conducting statistical analyses. It specifically enables users to download trend-related data in CSV format. The platform is equipped with four primary features:

1. Identifying current trends: The "Trending Searches" feature of Google Trends provides insights into the most recent popular searches worldwide.
2. Monitoring search interest over time: Google Trends has the capability to track the interest in a specific topic or keyword over time, which is determined by search volume.
3. Uncovering regional trending topics: Google Trends enables users to filter search data by specific countries and regions, allowing for the discovery of regional trending topics.
4. Performing keyword research: Google Trends proves to be an effective tool for conducting keyword research by exploring data.

This study employs Google Trends to conduct four separate statistical analyses. The first analysis examines the global popularity trends of both the abbreviation "ESG" and its full form, "Environmental, Social, and Governance." The results reveal a consistency in the outcomes of this analysis. The second analysis compares the global trends of "ESG" and "SDGs," identifying when "SDGs" started to trend. The findings suggest that "SDGs" have been less popular compared to "ESG." The third analysis explores the relationship between corporate governance and "ESG," indicating that "ESG" is gaining popularity while corporate governance is not. The final analysis investigates the trends of three key terms: "environment," "social," and "governance." The results demonstrate that social issues consistently garner more popularity than environment and governance, in that order.

Google Trends is a valuable tool that provides insights into the relative popularity or interest in key terms over time. This can serve as a proxy for public awareness and

sentiment, which are crucial factors influencing policy changes and corporate practices. For instance, an increase in search interest for a specific ESG issue could indicate growing public concern, which may in turn pressure corporations to adopt sustainable practices or governments to enact relevant policies. Conversely, a decrease in interest might suggest that the issue is no longer a priority for the public, potentially leading to less stringent corporate practices or policy changes. In the context of our study, we used Google Trends to track the relative interest in "lithium battery recycling" and "ESG." The comparative analysis of these trends could provide insights into how public interest in these topics has evolved and how this might correlate with changes in corporate practices or policy initiatives. However, it is important to note that while Google Trends can provide valuable insights, it should not be used in isolation. It is one of many tools that researchers and policymakers can use to understand complex phenomena. Therefore, our analysis also incorporates other data sources and research methods to provide a comprehensive view of the issues at hand.

Three countries predominantly control the battery production market: China is at the forefront with a substantial 45% share, trailed by Indonesia at 13%, and Australia at 9% (Llamas-Orozco et al. 2023). The strikingly low global lithium battery recycling rate of 1% suggests that no country has yet successfully implemented effective ESG strategies in this domain. In the recycling of lithium batteries, the three major countries are not fulfilling their production responsibilities.

Despite numerous studies challenging lithium battery recycling, the current recycling rate remains at just 1%. This paper aims to investigate the reasons behind the low recycling rate of lithium batteries and propose potential solutions to enhance recycling efforts. Utilizing the Google Trends tool, this paper analyzes public interest trends in the relative impact of ESG and SDGs, as well as the relationship between corporate governance and ESG. The analysis results highlight key areas that need to be addressed to improve recycling rates. The contribution of this paper lies in providing multifaceted solutions based on Google Trends analysis and a comprehensive literature review.

Statistical Analysis

This study employs Google Trends to analyze the relative popularity of specific keywords. This paper initially examines the trends of the SDGs, ESG, from 2004 to 2023 using Google Trends. This tool is capable of identifying time-series trends of keywords or phrases, thereby providing insights into public interest in related subjects. Following this analysis, the paper delves into an investigation of the impact of lithium batteries on Environmental, Social, and Governance (ESG) factors.

Figure 1 shows the world monthly trends of the keyword such as ESG and the phrase such as Environmental, Social, and Corporate Governance from 2004 to 2023. The result indicates that abbreviated ESG represents Environmental, Social, and Corporate Governance and increases its popularity from 2018 to 2023. Generative AI is used to visualize the csv dataset. Supplements with generated Python codes are attached to this manuscript.

Figure 2 presents a comparison of world ESG and SDG trends from 2004 to 2023. The analysis reveals that the peak interest in SDGs was reached in November 2021, while for ESG, it was in March 2023. Figure 3 illustrates the contrasting world trends of corporate governance and ESG from 2004 to 2023. It is evident that while the popularity of

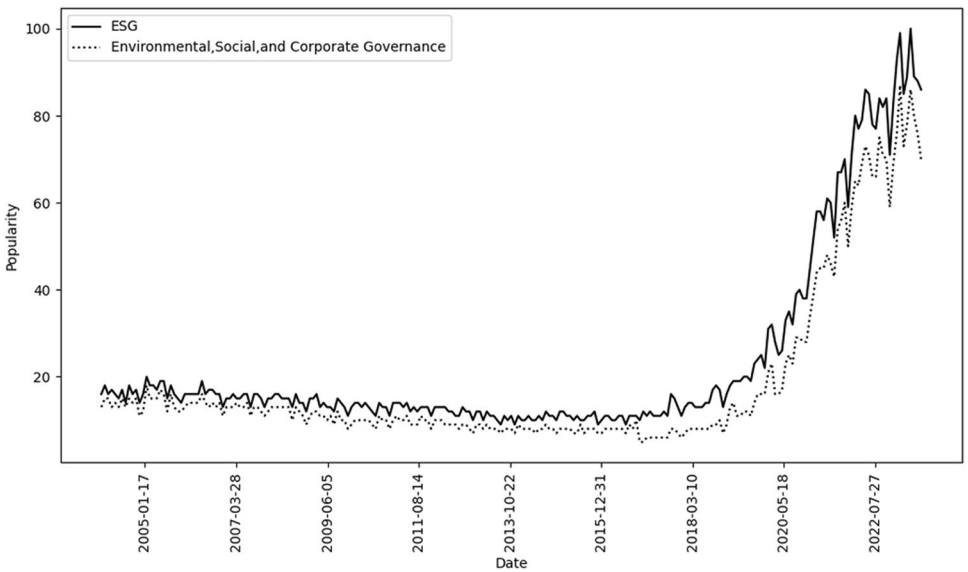

Fig. 1 ESG trends vs Environmental, Social, and Corporate Governance trends from January 2004 to September 2023

corporate governance has been on a decline, the interest in ESG has been steadily increasing during this period.

Finally, Fig. 4 shows the trends of three keywords of ESG such as environment, social and governance. The result

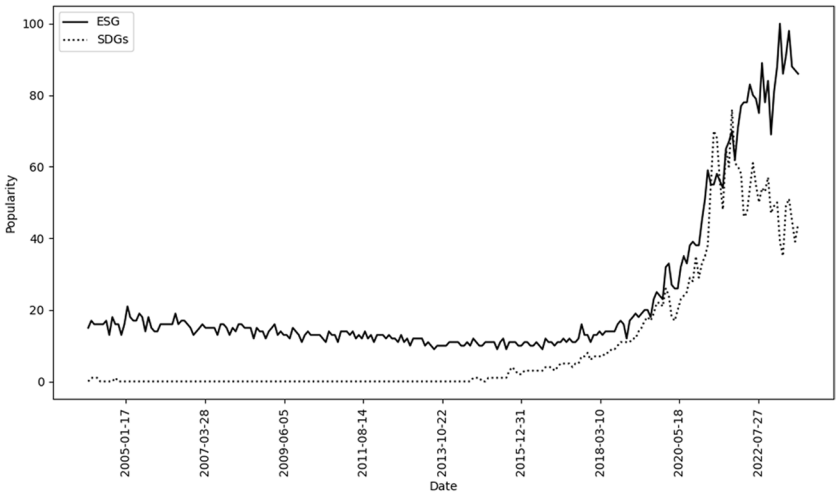

Fig. 2 ESG trends vs SDGs trends from 2004 to 2023

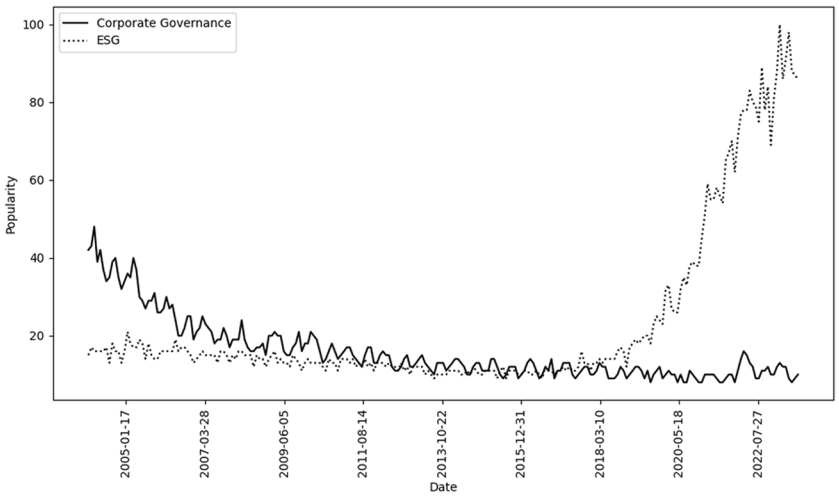

Fig. 3 Trends of corporate governance and ESG from 2004 to 2023

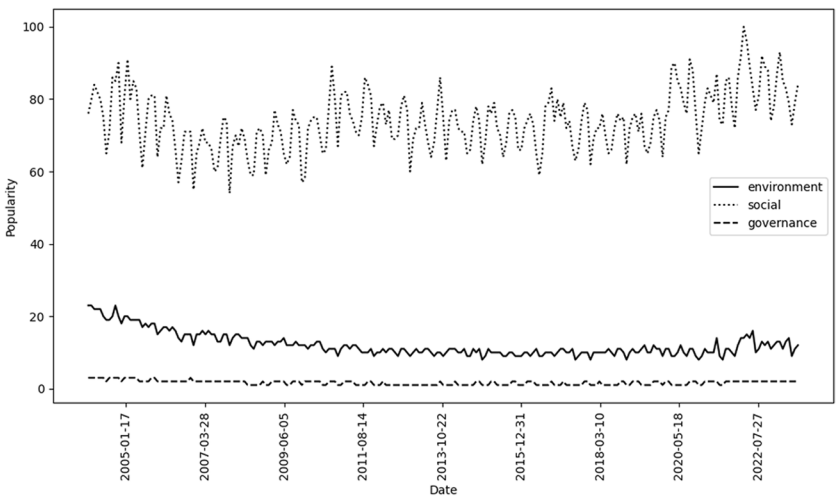

Fig. 4 Trends of three keywords such as "environment," "social," and "governance"

indicates that "social" keyword is constantly popular than "environment" and "governance" in that order. The results from Google Trends confirm that "governance" is among the least popular keywords in relation to SDGs and ESG.

The results indicate that Google Trends provides consistent data. It is observed that "SDGs" are less popular than "ESG." Furthermore, "ESG" is witnessing an increase in popularity, unlike corporate governance. Among the three key aspects—environment, social, and governance—social issues are consistently the most popular, followed by environment and governance.

Literature Review

Relying solely on specific databases limits the scope of peer-reviewed publications; however, one can gather a more extensive collection of peer-reviewed publications by utilizing Google's search engine over the Internet. This can be accomplished by using a range of intricate operators, including domain search, title search, phrase search, date search, and other search set operation functions available on the web. Importantly, a significant portion of the content from existing databases is also accessible online, thereby broadening the range of potential resources. The use of Google search operators for literature review is elaborated in detail (Takefuji 2024). The selection of publications can be efficiently conducted using set operations and exclude-operator on keywords and key phrases, as well as the date operator. This approach allows for a more targeted and time-relevant search of literature. For example, combining the domain search command with time constraint and keyword-phrase commands is useful for scraping specific time ranges and domains. For instance, the command "lithium battery" waste site:nih.gov after:2023–12-31 indicates a search within the nih.gov domain, constrained to after December 31, 2023, with the keyword "waste" and the keyphrase "lithium battery."

Elsevier provides access to the sciencedirect.com domain, while the Nature portfolio presents the nature.com domain. Google Scholar is one of the largest databases, containing both peer-reviewed and non-peer-reviewed publications, whereas the nih.gov domain hosts the largest collection of peer-reviewed publications. Seamlessly, Google's search operators can retrieve the desired literature review without the need to switch back and forth between databases or log into individual databases, simply by changing the search operator commands.

Lithium batteries have been used in a variety of small and large applications, including mobile phones, electric vehicles, and grid utilities. According to statista.com (Taylor 2023), the number of mobile users in 2022 is 7.26 billion, and 7.49 billion users will be forecasted in 2025. In other words, 7.26 billion mobile phones are currently used in the world.

A literature review was conducted on lithium battery and lead acid battery from the viewpoint of recycling to address critical issues in SDGs and ESG. The comparison between lithium and lead-acid battery recycling rates was conducted, revealing that the differences lie in recycling costs and technology. The paper highlights that CEOs and the general public are not fully aware of the importance of recycling from the perspectives of ESG and SDGs.

Yanamandra et al. investigated recycling of lithium batteries and lead acid batteries. Their study contrasted the recycling rate of lithium-ion batteries with a recycling rate of 1% versus a recycling rate of 99% for lead-acid batteries. The recycling rate of lithium batteries is currently very low, less than 5% within the European Union (Editorial 2019). The recycling rate for lithium batteries is low because it is more expensive to recycle them than to mine more lithium to make new batteries (Hagelüken and Goldmann 2022; Gutiérrez et al. 2022; Tabelin et al. 2021).

The SDGs are global goals set by the United Nations, and ESG is a rating system used by companies to measure the credibility of their ESG practices that are important to stakeholders, especially investors. In other words, from a circular economy perspective, recycling lithium batteries is important for profitable companies due to influencing their stock prices from a sustainable perspective.

Two literature reviews were conducted on (1) the impact of ESG on stock prices and (2) the relationship between lithium batteries and ESG. Therefore, this paper will consist of the results of the first literature review on the impact of ESG on stock prices and the results of the second literature review on lithium battery impact on ESG. Cost-oriented CEOs mining lithium cheaper than recycling disrupt circular economy. Many CEOs are not aware of the importance of ESG on stock prices and financial risks. Finally, the potential solution to current ESG issues for lithium batteries will be addressed in this paper. Digital passport, federal fundings, and global tax on CO_2 emissions may improve ESG.

The basis for rating the ESG of a company varies between different rating platforms (MSCI 2023; IOSCO 2021; Drempetic et al. 2020).

However, they all fall within one or more of the E, S, or G categories. For example, MSCI ESG Ratings aim to measure a company's management of financially relevant ESG risks and opportunities (MSCI 2023). They use a rules-based methodology to identify industry leaders and laggards according to their exposure to ESG risks and how well they manage those risks relative to peers. Their ESG ratings range from leader (AAA, AA), average (A, BBB, BB) to laggard (B, CCC). MSCI's ratings decompose ESG into its three thematic components: the environment, social responsibility, and corporate governance. They analyze metrics within

each of these key issue items and score the companies on each key issue from zero to ten, with zero indicating virtually no exposure and ten representing very high exposure to a particular ESG risk or opportunity (MSCI 2023).

The International Organization of Securities Commissions (IOSCO) does not offer a specific rating for ESG (Environmental, Social, and Governance). Instead, IOSCO has provided a set of recommendations for securities regulators to consider when overseeing ESG ratings and data product providers (IOSCO 2021). These recommendations are designed to address issues related to the relevance, reliability, and comparability of ESG data (IOSCO 2021).

Drempetic et al. (2020) published a study on ESG (Environmental, Social, and Governance) ratings in the Journal of Business Ethics. Their research utilized Thomson Reuters ASSET4 ESG ratings to examine the impact of firm size, the resources available to a company for providing ESG data, and the accessibility of a company's ESG data on its sustainability performance.

This study found that public interest in ESG has surpassed that of SDGs and corporate governance, as measured by Google Trends. Among the ESG components, social issues garnered the most attention, followed by environmental concerns and governance. The low recycling rate of lithium batteries poses a significant ESG challenge due to environmental and social implications. Notably, many CEOs are unaware of the impact of ESG on their company's financial performance. Ultimately, the findings from Google Trends corroborate the outcomes of the literature reviews.

ESG Impact on Stock Prices

A literature review on the impact of ESG on stock prices was conducted to demonstrate the strong link between ESG and stock prices.

Li et al. (2022) studied the relationship between ESG performance and stock prices during the COVID-19 pandemic. Reputation and insurance effects are important mechanisms through which ESG performance can affect stock prices. Their result is consistent with the view that investors may take ESG performance as a signal of risk mitigation during a crisis.

Zhou and Zhou (2021) revealed that the stock market experienced a significant impact due to COVID-19 and that the company's stock prices became more volatile. However, the stock prices of some companies with good ESG performance have remained relatively stable. Xu et al. found the similar relationship between ESG and stock price such that the mechanism is that companies choose to disclose ESG information to mitigate information asymmetry issues and increase their reputational capital, thereby reducing the risk of future stock price crashes (Xu et al. 2022). Boadstock et al. examined ESG performance during the COVID-19 financial crisis, questioning if investors see it as a signal for future stock performance or risk mitigation. Using data from China's CSI300 constituents, they found that (i) high-ESG portfolios generally outperform low-ESG ones, (ii) ESG performance mitigates financial risk during crises, and (iii) its role is less significant in normal times, highlighting its importance during crises. Results are framed in the context of ESG investment practices. Broadstock et al. (2021) suggested that ESG performance could save the financial crisis. Park et al. (2022) concluded that many studies have found that companies with high ESG are strong against risk.

Ji et al. (2022) recommend that (1) ESG assessment systems need to be designed and improved to take into account China's regional and industry-specific characteristics, (2) commercial banks should be encouraged to take the lead in expanding ESG investments, and (3) oversight of ESG information disclosure should be strengthened and commercial banks should be actively and effectively coached to continuously improve their ESG information openness.

Kim et al. (2022) investigated whether ESG can drive the sustainability of multinational corporation's subsidiaries. Their results of subsidiaries of multinational corporations showed that ESG improves the financial and non-financial performance of subsidiaries (Kim et al. 2022).

Yoo et al. (2021) study whether the performance of sustainability activities matters during financial crises. Their results indicate that during a pandemic, an increase in the ESG score, especially the E-score component, is associated with higher returns and lower volatility.

As the percentage of green investors increases and the quality of ESG information improves, the informativeness of the price on financial payoffs may decrease, and the cost of capital may increase (Goldstein et al. 2021). ESG mitigates financial risk, yet this concept is not fully grasped by CEOs. The Google Trends results for the less popular keyword "governance" related to ESG and SDGs corroborate the current stance of CEOs on ESG financial risk.

Meshram et al. (2020) reported that evaluating the environmental impact of lithium and lead-acid batteries involves a complex interplay of numerous factors. Lead-acid batteries are 99% recyclable, but the process can lead to environmental contamination and human exposure to lead, thereby causing health issues. On the other hand, lithium-ion batteries are currently recycled at 1%, but they do not contain dangerous materials like lead. Yudhistira et al. (2022) reported that the lithium-ion batteries have fewer environmental impacts than lead-acid batteries for the observed environmental impact categories.

With the global demand for batteries on the rise, recycling discarded lithium batteries has emerged as a significant solution. Yet, this process results in substantial wastewater production, laden with high levels of heavy metals and acids. Wu et al. (2023) have clearly stated that without a proper

recycling process, the implementation of lithium battery recycling could pose serious environmental threats, health risks, and result in wastage of resources.

The higher energy density of lithium batteries could potentially lead to a lower environmental impact per unit of energy stored and delivered. However, the overall environmental impact also depends on factors such as the methods used for mining and processing the raw materials, the lifespan of the batteries, and the processes used for recycling or disposal.

Collectively, existing research suggested that ESG improves stock prices and reduces financial risks such as the COVID-19 pandemic. In other words, many companies in the world are not aware of the importance of ESG on their stock prices and financial risks.

ESG of Lithium Batteries

To demonstrate the importance of the role of lithium batteries in ESG, a literature review was conducted on the impact of lithium batteries on ESG.

In the circular economy, metals such as cobalt (Co), nickel (Ni), and lithium (Li) in lithium batteries; platinum group metals (PGM) in catalysts; or precious metals, copper (Cu), and tin (Sn) should be recycled (Hagelüken and Goldmann 2022). In many cases, significant ESG cost savings are achieved by non-compliant recyclers due to externalization of ESG costs, but low-quality processes often outweigh their lower recycling yields. Mining is much cheaper than good recycling (Hagelüken and Goldmann 2022).

Lèbre et al. (2020) investigated the social and environmental complexities of extracting energy transition metals (Lèbre et al. 2020). The ESG risk context is modelled using seven dimensions: waste, water and conservation, land uses, communities, and social vulnerability, and an overarching governance dimension. Their results showed that 84% of platinum resources and 70% of cobalt resources are in high-risk situations. In other words, the impact of lithium batteries on ESG risk is very high.

Large-scale recycling of lithium-based batteries, recovery and removal of Li from contaminated areas, and accumulated waste, particularly e-waste, is still a challenge (Martins et al. 2022a).

Martins et al. (2022b) investigated the long-term toxicity of Li and Li-MPs mixtures to the freshwater zooplankton species *Daphnia magna*. Their result showed that (1) warmer water increased the long-term toxicity of Li and Li-MPs mixtures to *D. magna*; (2) high light intensity (low UV) also augmented the toxicity of Li and Li-MPs mixtures; (3) temperature rise and chemical stress interact synergistically in all the scenarios; (4) light intensity rise and chemical stress interact mainly synergistically; and (5) 0.08 and 0.1 mg/L of Li, alone and in Li-MPs mixtures caused population extinction. Lithium batteries, when improperly disposed of, can lead to environmental contamination. The release of lithium and other toxic chemicals from these batteries can pollute soil and water sources. Martins et al. found that lithium and lithium microplastics mixtures increased toxicity in freshwater zooplankton species *Daphnia magna*, especially under warmer water and high light intensity conditions. This indicates that lithium contamination can have severe ecological impacts, potentially leading to the extinction of sensitive aquatic species. Additionally, the interaction of temperature rise and chemical stress can exacerbate the environmental harm caused by lithium batteries. In other words, lithium batteries should be recycled without contaminating the environment by lithium.

Remotely sensed measures of surface water levels and a 30-year dataset on flamingo abundance using structural equation modelling revealed that lithium mining for batteries with climate change influences flaming abundance in lithium triangle of the Chilean Andes (Gutiérrez et al. 2022). In other words, lithium mining is cheaper than recycling, but it should be reconsidered from an ESG perspective.

The lithium market is not entirely consistent with theoretical notions of renewable energy market dynamics (Altiparmak 2022). Energy geopolitics requires that traditional explanations of energy security be modified for China's new market environment. In other words, without an ESG perspective, companies involved in the lithium market will be severely impacted by declining stock prices.

The exact costs of lithium mining and recycling can vary depending on several factors such as location, technology used, and market conditions. As of October 2020, trading of battery-grade LiOH and LiCO3 based on lithium mining were around US $8500–9500 per ton (Tabelin et al. 2021). The economic worth of lithium-ion battery recycling has been estimated as US $22,000 per ton, based on the values of lithium and cobalt (Garcia et al. 2023). This means that recycling lithium batteries is at least twice as expensive as producing new batteries. This is due to lacking in low-cost recycling technology (Zhang 2024) and investment in recycling for lithium batteries (Ralls et al. 2023).

Based on the literature review, lithium mining is cheaper than recycling. Many companies involved in the lithium market are based on cost-oriented policy so that their priority on recycle is very low. In other words, cost-oriented CEOs mining lithium cheaper than recycling disrupt the circular economy. Lithium batteries and recycling lithium batteries are essential for policymakers and CEOs to fulfill the goal of ESG.

Potential Solutions to ESG for Lithium Batteries

The literature review results revealed that recycling lithium batteries is more expensive than producing new batteries

(Hagelüken and Goldmann 2022; Gutiérrez et al. 2022; Tabelin et al. 2021). This finding suggests that current policies incentivizing the production of new batteries may need to be reevaluated.

The author recommends implementing policies that provide financial incentives for recycling lithium batteries, such as tax benefits or subsidies for companies that invest in recycling technologies. Furthermore, the literature indicates that CEOs are not fully aware of the ESG importance of lithium batteries and its impact on financial risks (Zhou and Zhou 2021; Xu et al. 2022; Broadstock et al. 2021; Park et al. 2022). This lack of awareness could be addressed through mandatory ESG training for executives and the implementation of policies that require companies to disclose their ESG risks related to lithium batteries. These recommendations are based on evidence from the peer-reviewed literature and trusted organization documents.

In 2020, the European Union has proposed new battery regulations, requiring access to battery management systems and mandating digital battery passports, carbon footprint declarations, and maximum thresholds. In addition, the extended producer responsibility law for end-of-life vehicles proposes to impose specific material recycling (Richter 2022).

Using an innovative geochemical approach based on Li isotopic analysis of raw and processed materials, Desaulty et al. (2022) showed that Li isotopic "fingerprinting" is a useful tool for determining the origin of lithium in rechargeable lithium-ion batteries. This provides the basis for a new method to reliably authenticate the lithium contained in lithium-ion rechargeable batteries (Desaulty et al. 2022).

For a circular economy to succeed, it is a prerequisite for excellence in metallurgy and chemistry (Editorial 2022). The ultimate recycling technology lies in learning how to break down materials at the atomic level, breaking down molecules and reusing atoms. Funding agencies should be looking at promising approaches, from metal alloys to plastics (Editorial 2022).

Cox et al. (2022) found that under a stronger carbon pricing initiative, commodities such as coal could be taxed at more than 150% of their current commodity value, which would accelerate the transition to renewable energy sources and thus benefit demand for mined metals.

The Battery Passport initiative in the European Union (EU) is designed to increase transparency and enable sustainable and circular value chains for batteries (Nie et al. 2023; WEF 2023). The following are some of the impacts caused by battery passports:

1. Sustainability and circularity: The passport is designed to record and share extensive data across the entire battery value chain via a digital platform. This data will facilitate the development of production and value creation processes that adhere to sustainable and circular principles.
2. Consumer decisions: The passport aids consumers in making informed decisions by providing access to data for specific actors throughout the value chain.
3. Life cycle extension: The passport promotes the extension of the battery system's life cycle through cascaded use and encourages the recycling of raw materials and components at the end of the life cycle.
4. Reduced costs: The availability of improved data is anticipated to lower costs for circular business models throughout the battery's life cycle.
5. Environmental impact: The battery passport is intended to significantly reduce greenhouse gas emissions and enhance the environmental performance of battery production and usage.
6. Supply chain transparency: The EU has implemented regulations to foster a circular battery economy, which includes the introduction of "battery passports" to enhance traceability.
7. End-of-life management: The passport maintains a detailed record of the battery's life cycle, including data on collection and recycling. This allows for efficient management of end-of-life batteries, ensuring their proper disposal and minimizing environmental impact.

Yu et al. (2022) recommended and reported that to accelerate lithium-ion battery (LIB) recycling, the government should prioritize funding for research, pilot projects, and market initiatives. This includes matching federal funding for LIB collection with battery R&D, supporting pilot projects to fill data gaps, and implementing market pull policies. Additionally, deposit reimbursement schemes could incentivize proper disposal of spent LIBs. Establishing a comprehensive battery recycling data platform and effective regulations could further enhance the recycling process.

Taseska et al. (2023) reported that the uncertainties surrounding the development of policies to mitigate environmental impact and their associated costs pose a significant challenge to industry forecasts for sustainable manufacturing. There is a pressing need for substantial investments in research funding in both academia and industry for the development of emerging and future solutions. For instance, in the USA, the federal funding allocated for the development of sustainable successor technologies is considerably lower than that for medical research. It is crucial that government funding be significantly increased to facilitate fundamental research, which is essential for hastening the discovery of new catalysts and environmentally friendly catalytic processes.

Based on the literature review, potential solutions to ESG of Lithium batteries are (1) mandating digital passports, (2) Li isotopic analysis allows Li isotopic "fingerprinting" for

reliable authentication, (3) enhancing recycling technology with federal fundings, and (4) a global tax on carbon emissions to the mining industry. However, ESG of lithium batteries is very slow. The progress of ESG in the lithium battery industry can be slowly due to several reasons. One reason may be that lithium production has a significant carbon footprint, which has raised concerns among automakers and investors. Despite playing a key role in the energy transition, the lithium sector is recognizing that it is not enough to escape scrutiny.

Conclusion

A comparison of world ESG and SDG trends from 2004 to 2023 revealed that the peak interest in SDGs was reached in November 2021, while for ESG, it was in March 2023. The contrasting world trends of corporate governance and ESG from 2004 to 2023 showed that while the popularity of corporate governance has been declining, the interest in ESG has been steadily increasing. The trends of three keywords of ESG—environment, social, and governance—indicate that the "social" keyword is consistently more popular than "environment" and "governance." Google Trends results confirm that "governance" is among the least popular keywords in relation to SDGs and ESG.

Existing research indicates that ESG (Environmental, Social, and Governance) practices can enhance stock prices and mitigate financial risks, such as those experienced during the COVID-19 pandemic. Therefore, it is crucial for CEOs globally to recognize the significance of ESG and its impact on financial stability. Lithium batteries and their recycling are vital for achieving ESG goals. Policymakers must address ESG issues related to lithium batteries by mandating digital passports, improving recycling technology with federal funding, and implementing a global tax on carbon emissions in the mining industry.

Lithium batteries are widely used, but their recycling rate is only 1%, far below the global targets set by the United Nations. Many CEOs are unaware of the importance of ESG on stock prices and financial risks. Cost-focused CEOs who prioritize cheaper lithium mining over recycling disrupt the circular economy. Potential solutions to enhance the ESG of lithium batteries include mandating digital passports, using Li isotopic analysis for reliable authentication, improving recycling technology with federal funding, and implementing a global tax on carbon emissions in the mining industry. These measures can help policymakers and CEOs achieve ESG goals.

Without improving lithium battery recycling, a new environmental issue will emerge due to the large number of disposed batteries. As the percentage of green investors rises and the quality of ESG information improves, the informativeness of financial payoffs may decrease, and the cost of capital may increase (Goldstein et al. 2021). Broadstock et al. (2021) found that ESG performance during the COVID-19 financial crisis could help mitigate financial crises.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42824-024-00146-5.

Author Contribution YT completed this research and wrote the program and this article.

Data Availability Data is included in this manuscript.

Code Availability Code is attached in this manuscript.

Declarations

Research Involving Human Participants and/or Animals Not applicable.

Informed Consent Not applicable.

Conflict of Interest The author declares no competing interests.

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