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**\*Correspondence**

Ahed J Alkhatib  
Email:  
ajalkhatib@just.edu.jo

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## The Environmental Impact of Lithium-ion Batteries and Alternatives

**Ahed J Alkhatib<sup>1,2,3\*</sup>**

<sup>1</sup>Department of Legal Medicine, Toxicology and Forensic Medicine, Jordan University of Science & Technology, Jordan.

<sup>2</sup>International Mariinskaya Academy, department of medicine and critical care, department of philosophy, Academician secretary of department of Sociology.

<sup>3</sup>Cypress International Institute University, Texas, USA.

**Abstract:**

Electric vehicles (EVs) are becoming an integral part of modern transportation, offering lower operating costs, reduced emissions, and lower noise levels. As the number of electric vehicles increases, the demand for reliable energy storage will also increase. These energy sources are largely lithium-ion batteries. They support grid stability of electricity systems, portable electronics, and residential storage. Lithium-ion technology is a high-performance solution. However, its production, usage, and end-of-life have an impact on the environment and health. A thorough analysis of energy, CO<sub>2</sub> emissions, and economic variables is missing. Life Cycle Assessment (LCA) is already an established approach for calculating environmental impacts from the extraction of a resource to its disposal. More and more, with the help of advanced software and environmental awareness, LCA is used in the automotive. Battery capacities of electric vehicles (EVs) are improving and their prices are falling, making them competitive with internal combustion engine (ICE) two-wheelers. But, there are trade-offs with emissions, resource use, and toxicity. This paper presents the LCA (life cycle assessment) results for EVs, buses, and trains compared with ICE variants using five different electricity generation mixes. The results inform policymakers, producers, and consumers on the environmental performance and future potential of EV technology.



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## INTRODUCTION

The integral role of lithium-ion batteries within current technology is unambiguous (Arshad *et al.*, 2022). The power innumerable devices from phones to cars, have been called 'green batteries' by some due to their application as energy buffers from renewable sources, and are pivotal in the quest to make electric vehicles a day-to-day reality (Chordia *et al.*, 2024). However, it is necessary to question the 'green' credentials of lithium-ion batteries (Lai *et al.*, 2022). Although not as harmful as nickel-cadmium, with their inclusion as part of consumer electronics limiting the chance of them simply being discarded after use and the creation of a dedicated initiative to manage the disposal of electric vehicle batteries, their parts can still be harmful to the environment (Li *et al.*, 2022; Alawnah *et al.*, 2024). Cobalt, found in the form of lithium cobalt oxide, has mutagenic, carcinogenic, and respiratory effects (Porzio and Scown, 2021). Most of the world's cobalt is sourced from the Democratic Republic of the Congo and is linked to child labor and corruption (Alkhatib *et al.*, 2014a; Chen and Hsieh, 2023). A projected only 2% of battery waste was being recycled (Lai *et al.*, 2023). The most carbon and energy-intensive point of a lithium-ion battery's life cycle is during its production (Engels *et al.*, 2022). Mining, purification, and electrode coating are resource-intensive processes associated with negative environmental and safety concerns (Sadhukhan and Christensen, 2021). Litres of water are required to extract just one kilogram of lithium from brines (Degen and Schütte, 2022).

The aforementioned avoids the fact that the world's population must meet the ever-growing demand for more and "better" technology (Fleischmann *et al.*, 2023). To limit the extent of global warming, coal mining must end by 2040, yet simply considering electric vehicles, to commit to a 2°C target means "downsizing energy hogs and petrol-head culture." So, already over workforce intensity jobs within the coal industry can be avoided (Alkhatib and Al Zailaey, 2015; Zhao *et al.*, 2021). Along with other environmental benefits, the adoption of electric-powered transport enables the electrification of machinery, further reducing

reliance on coal-powered stations (Crespo *et al.*, 2022). Plans have been outlined as part of a strategy to make battery packs and install battery recycling plants by 2025 (Nurdiawati and Agrawal, 2022). This national capability should facilitate the creation of a "closed loop for batteries," wherein "battery material is recycled and used in the manufacture of new batteries" (Giosuè *et al.*, 2021; Nguyen-Tien *et al.*, 2022). Currently, market incentives for battery manufacturers emphasize final consumer performance and cost; this proposal hopes to fast-track setting standards requiring "secondary life cycling and disposal standards of lithium-ion batteries (Nie *et al.*, 2023).

## Lithium-ion batteries: Composition and environmental impact

In 1991, Sony developed lithium-ion batteries (LIBs) for commercial use as a secondary battery, and since 2000, they have been the most common type of rechargeable battery for mobile electronic devices (Tivander, 2016). The driver for the event was pro-environment; there was no interest imaginable to compete for power plants (Mohammadi and Saif, 2023). As the benefits of electric vehicles become increasingly apparent, many expect buyers to shun traditional cars with internal combustion engines at an accelerated pace (Salgado *et al.*, 2021). As governments everywhere look to implement more expansive green policies, it increasingly appears a question of when, rather than if, battery power will overtake internal combustion, potentially within just the next two decades (Hu *et al.*, 2021). Concomitantly, commodity players can be seen staking out their ground across a supply chain, from lithium mining to cathodes and anodes (Harland, 2016). To manufacture lithium-ion batteries, which account for the majority of electric vehicle batteries, batteries for plug-in hybrids, electric bicycles, and storage batteries, lithium cobalt oxide ( $\text{LiCoO}_2$ ) is selected for the positive electrode, where cobalt metal makes up about 60% of the active material; lithium manganese oxide ( $\text{LiMn}_2\text{O}_4$ ) with cobalt and phosphorus as components is extracted for the household use (Lai *et al.*, 2022). The positive electrodes of most batteries for mobile phones and PCs are mainly made of

cobalt (Dunn *et al.*, 2021). As for recent environmentally friendly power-consuming investigations, the viability of the eco-friendly power demand is of paramount concern. LIBs are one type of eco-friendly electric storage device that cuts out cobalt, a kind of rare metal (Yang *et al.*, 2021). Theoretically, the negative effects of LIBs on the reduction of external cost in electricity manufacturing decrease by pulling some rare metal cobalt (Zhang *et al.*, 2022). In actuality, the potential of LIBs for alternative eco-friendly power is subject to serious discussions because it remains to be debated as to whether LIBs can or cannot ration the rare metal and whether the vehicles are environmentally harmonious (Chen *et al.*, 2022).

### Components of Lithium-ion batteries

Lithium-ion batteries store and discharge electricity by shuttling lithium ions back and forth between the anode and cathode, where they're embedded in a structure (graphite on the anode, lithium cobalt oxide on the cathode) and electrolyte solution containing the lithium salt (Koech *et al.*, 2024). A separator is put between the anode and cathode to keep them from fusing while allowing transfer of ions (Du *et al.*, 2024).

According to the first law of thermodynamics, energy cannot be created or destroyed, only converted from one form to another (Harland, 2016). This helps explain the chemistry of how lithium-ion batteries operate (Xu *et al.*, 2023). One form of energy is chemical potential energy, which is stored in the atomic bonds of the molecules that compose the battery (Gao *et al.*, 2022). Chemical energy is converted to electrical energy when the battery is discharging; the lithium ions are stripped from the cobalt, migrate to the graphite, and release an electron along the way (He *et al.*, 2021). This electron is then captured by an external circuit to power a device (Rudola *et al.*, 2021). The reverse can be done to charge a battery. When a battery is charged, electrical energy is provided to the battery, and this energy is stored as chemical energy in the bonds of the battery's molecules (Lebrouhi *et al.*, 2022). Li-ion batteries are used in many applications (Rouholamini *et al.*, 2022). They are the dominant battery technology for portable

electronics like cellphone batteries and laptop batteries, but are also emerging as the technology of choice for electric vehicles and grid storage; they're even going to be used on the Orion spacecraft. For these applications, they dominate storage technologies as a result of their high energy density (Park, 2024).

Amid a rapidly expanding market and heightened interest in technology involving lithium-ion batteries, it's only natural to delve into the inner workings of what makes a lithium-ion battery, well, a battery (Zackrisson *et al.*, 2018). While the chemical properties of the individual components were alluded to, it's important to expand on them further (Nyamathulla and Dhanamjayulu, 2024). At risk of oversimplifying, the end goal of a battery is to store energy and then discharge it in a controlled manner (Olabi *et al.*, 2022). This process is accomplished in a lithium-ion battery by the shuttling of lithium ions between the anode and the cathode (Salameh *et al.*, 2022). On one of these surfaces, the lithium ions are embedded in a structure, such as graphite on the anode-end or lithium cobalt oxide on the cathode-end (Chen *et al.*, 2023). What allows this process to occur is an electrolyte solution containing a lithium salt that facilitates ion transport while not being reactive with the other components (Makhadmeh *et al.*, 2021). To keep the anode and cathode from physically fusing while still allowing for the transfer of lithium ions, a separator is placed between them (Zackrisson *et al.*, 2018).

### Lifecycle analysis of Lithium-ion batteries

The environmental impact of lithium-ion batteries and potential alternative battery technologies is argued (Xu *et al.*, 2024). Lithium-ion batteries are currently the go-to power source for portable electronics and electric vehicles, but their disposal creates a safety hazard (Simpson *et al.*, 2024). This debate aims to recognize the whole environmental cost of these batteries and to suggest safe and sustainable future equivalents (Chen *et al.*, 2023).

Lithium-ion batteries are energy storage systems that rely on reversible electrochemical reactions

to transfer lithium ions and electrons between active materials and the cell's electrodes (Mrozik *et al.*, 2021). The growing popularity of lithium-ion batteries is entirely due to their unique combination of gravimetric and volumetric energy density, which can be much higher than that of other rechargeable batteries (Melchor-Martínez *et al.*, 2021). In the case of electric vehicles and large-format energy storage systems, millions of lithium-ion batteries might be connected in a single large bank (Sankar *et al.*, 2024). The disposal of lithium-ion cells is a significant safety hazard due to their chemical energy capacity, and it poses a large ecological problem due to metal pollution (Miao *et al.*, 2022). To evaluate the environmental cost of lithium-ion cells, their entire life cycle from material extraction, over production and use, to recycling or disposal, must be analyzed (Golmohammazadeh *et al.*, 2022).

This paper serves as the lifecycle analysis of lithium-ion batteries. Lifecycle analysis (LCA) is a standard tool for evaluating the environmental cost of a product or process (Chen *et al.*, 2022; Lai *et al.*, 2022). This analysis moves through the life of one size of lithium-ion polymer cell, covering six stages: raw material extraction and production of input materials, packaging and transportation of parts, battery assembly and formation, transporting the new fully charged cell to a device manufacturer, the use of the cell in the host device, and end-of-life (recycling, landfill, or incineration of the cell) (Lai *et al.*, 2022; Chordia *et al.*, 2024). The environmental cost of each stage is represented by tabulating the energy use and different emissions (Li *et al.*, 2022). Major findings indicate that the single largest contributor to the carbon footprint of the lithium-ion battery is the input energy used to produce electrodes (Fahimi *et al.*, 2022). It is also recognized that the efficiency of the host device to which a lithium-ion battery is connected is of paramount environmental concern (Lander *et al.*, 2021).

## Environmental concerns and challenges

Preoccupation with carbon footprints has thrown a critical light on lithium-ion batteries, universally perceived as the technological fix for climate

change (Domingues *et al.*, 2024). Despite their EV (electric vehicle)-friendly benefits, these lightweight, high-energy-density power sources entail environmental as well as social externalities (Domingues and de Souza, 2024). Life cycle assessment often pivots on pollution prevention and energy saving, in which the lithium-ion battery is generally portrayed as an effective mitigation strategy for greenhouse gas emissions (Roa and Rosendahl, 2023). Dynamically complex, life cycle assessment serves as a symbolically dense placeholder for the representation of governance mechanisms to cope with the unprecedented number of pollutants in the late modern era (Paul *et al.*, 2024). Rhetorically, the battery industry lauds itself for being on the cutting edge of "sustainability," and uncritically it is reproduced by mainstream media, energy corporations, and governmental bodies (Nie *et al.*, 2023).

Disputably, however, the substantial energy inputs required to make the lithium-ion battery systemically ineffective in reducing greenhouse gas emissions. Conventional lithium-ion battery packs need 238-320 MJ/kWh. Such a large amount usually involves contamination by carcinogenic and mutagenic elements (Alkhatab *et al.*, 2014a; Zhang *et al.*, 2024). From a single prism, the energy invested doesn't yield the corresponding payback. Taking Norway as a best-case scenario, where 98% of electricity generated comes from renewable sources, emissions are still above those from a 50 km/L gasoline car. For comparison, Norway is one of the most hydropower-reliant countries, housing Wolfsberg, the largest Lithium open pit mining facility in Northern Europe since 1982 (Zackrisson *et al.*, 2018).

## Alternatives to Lithium-ion batteries

The environmental impacts of the broad commercialization of lithium-ion battery (LIB) technologies are worsening with the adoption of a global green technology-based society (Arshad *et al.*, 2022; Lai *et al.*, 2022). The environmental impacts of LIBs fall into two representative categories (Chen *et al.*, 2023). The first is the direct environmental impact, which includes degeneration and contamination

due to fabricating, using, and disposing of LIBs (Chordia *et al.*, 2024). The second is the indirect environmental impact, which includes the extraction and purification of raw materials and the parameter changes of ecosystems (Sankar *et al.*, 2024). Considering both the direct and indirect environmental impacts of commercial products based on LIB technologies, correspondingly, alternative energy sources are sought (Shekhar *et al.*, 2022; Domingues and de Souza, 2024).

One potential alternative energy source is aluminum, which is remarkable for its qualities of lightness, low costs, high capacity, and environmental friendliness (Raabe, 2023). Al is the most abundant metallic resource in the Earth's crust, and it is strikingly connected with the sustainable development linked with electric vehicles (EVs) and energy storage systems (ESSs) (Boran *et al.*, 2013). The LIB, which is commercialized as a representative battery of energy and power-demanding goods, depends on limited raw materials with a complex collecting system (Ali, 2023). Therefore, it is a challenge for clean and sustainable battery production to find an alternative energy source that is low-cost, environmentally friendly, and sustainable, and is widely and easily available (Closset *et al.*, 2021). Moreover, globally ongoing research is needed for developing alternative battery technologies that could lessen the environmental impacts of broadly commercialized LIB technologies (Altaş *et al.*, 2024). To find the most suitable approach in research and development, understanding the direct and indirect environmental impacts of current battery technologies and comparing these with alternative battery technologies will be a timely and useful step (Tang *et al.*, 2024).

## Sodium-ion batteries

The lithium-ion battery, the technological workhorse of clean energy, hasn't always had the positive environmental record it enjoys today (Zuo *et al.*, 2023). With this context in mind, the environmental costs and benefits of a promising solution to this dilemma, sodium-ion batteries, are evaluated (Glushenkov, 2023). It's a gray, fall morning in Portland, US, and the news

outlets are flooded with the same headline: "World's Biggest Lithium Mine Approved in Nevada Desert." Two hours south of this Cascadian city (Zhang and Ran, 2021), Thacker Pass, once a pristine and wildlife-filled sagebrush steppe, will come to house North America's largest carbon lithium mine (Lu *et al.*, 2021). The mine will rip up 18,000 tons of earth, destroying over 5000 acres of habitat for pygmy rabbit, sage grouse, pronghorn, and mule deer (Zuo *et al.*, 2023). Yet, curiously, it's happened in what's arguably the most liberal of U.S. states. Why? Tesla and lithium-ion battery giga-plants have laid down stakes in Nevada, drawing a 2025 projection of 600% growth in lithium demand (Wanison *et al.*, 2024). A balanced, realistic approach to sodium-ion batteries is engaged (Lou *et al.*, 2021). Sodium batteries are sold as "drop-in" — to the same category as lithium-ion batteries, which means there is no need for large changes in the electrochemical systems. Considering the fact that the technology is already established in lithium-based systems, a possible more rapid upscaling and implementation in practical applications can be achieved (Ren *et al.*, 2023). Sodium batteries operate on the same basic principles as lithium-ion batteries. Indeed, they are marketed as drop-in lithium infrastructure (Zhao *et al.*, 2023). In terms of both chemistries rock the same architecture, similar working mechanism, and thus shared components (anode, cathode, and electrolyte) (Kanwade *et al.*, 2022). However, if sodium is substituted for lithium, the new material has its environmental costs slashed (Zhao *et al.*, 2023).

## Solid-state batteries

When discussing electric cars, the topic of batteries can hardly be avoided (Kalungi *et al.*, 2024). As battery technology stands, the most widely used form of electricity storage in cars is the lithium-ion battery (Mishra *et al.*, 2022). Although these batteries are much less polluting than internal combustion engines, they are far from perfect for the environment (Mohanty and Devi, 2023). The extraction, refining, and disposal of lithium and cobalt all lead to enormous amounts of toxic waste, as does the liquid electrolyte contained in the batteries.

Furthermore, in April and May 2019, fires broke out at two large energy storage facilities (Miao *et al.*, 2022). Combined, these incidents caused more than \$40 million in damage and released 120 tons of toxic materials (Chandra *et al.*, 2022). Solid electrolyte batteries do not contain this liquid electrolyte. Instead, a layer of solid electrolyte is placed between the cathode and anode (Beales *et al.*, 2021). Due to this, cells are generally lighter, and the battery provides a higher energy output (Chan *et al.*, 2021). When compared to the liquid equivalent, the electrodes of a solid battery degrade at a significantly slower rate (Hasan *et al.*, 2023). Presently, on the market, solid batteries have cycle lives seven times longer than their liquid equivalent. Besides the higher energy output and longer-lasting electrodes, solid electrolyte batteries are also intrinsically safer than their liquid counterparts (Zhang *et al.*, 2021).

## Flow batteries

Similar to Lithium-Ion and lead-acid batteries, flow batteries consist of a stack of electrodes and an electrolyte that facilitates the transfer of ions within the system (Horn *et al.*, 2021). The main distinction lies in the operational principles of flow batteries, which store an electrical charge by storing the active species in large tanks and pumping them through the system using both anode and cathode half cells (Zhao *et al.*, 2015). As a result, the energy capacity of flow batteries can be easily decoupled from the limited power characteristics of solid-state batteries, allowing them to provide long-duration energy solutions (Gupta *et al.*, 2023). Recently, advances in novel cell design and electrolyte fabrication have brought renewed interest in the benefits of flow battery technology (Chang *et al.*, 2024). Moreover, materials like vanadium present a far longer estimated availability compared to the rapidly diminishing cobalt stores that lie at the heart of the most common Li-ion batteries (Gao *et al.*, 2024). This is particularly relevant to the toxicity of the batteries and their disposal at the end of their life (Xu *et al.*, 2024).

Although some futurists lauded the potential of flow batteries for applications that demand extended durations, they have struggled to

become a viable option in the market (Roth *et al.*, 2022). Critics pointed out how low efficiency and energy density have detracted from the overall appeal of the technology (Shafique *et al.*, 2022). In general, flow batteries are 25-45% less efficient than lithium-ion batteries across the range of applications (Olabi *et al.*, 2023). Another common criticism is the relatively low energy density of flow batteries, with up to an order of magnitude less storage per cubic meter than common Li-ion batteries (Tang *et al.*, 2023). This fear has only been confirmed by the popular choice to install lithium storage systems instead of their flow equivalents. So, despite the flurry of research interest, the question remains as to what niche these could occupy in the emerging energy market (Dieterle *et al.*, 2022).

## Comparative environmental impact assessment

Battery technology has gained significant attention in the public discourse as part of the increasing interest in improving energy systems towards environmental sustainability (Rys *et al.*, 2024). As a result, various battery technologies are undergoing rapid development to displace the conventional lead-acid batteries and cater to diversified energy storage demands (Juanico, 2024). This section aims to evaluate the comparative environmental implications of lithium-ion batteries, conventional lead-acid batteries, and some emerging alternatives, including sodium-sulfur and various types of flow batteries (Vangapally *et al.*, 2023). The scope of comparison takes into consideration the frequency regulation application of the batteries in the Northern Illinois region (Pawar and Kolte, 2022). Energy efficiency, carbon footprints, and environmental impacts related to the extraction of battery materials are among the factors concerning the environmental performance assessment (Makola *et al.*, 2023). A series of technical and environmental implications is synthesized to provide an overall understanding of the sustainable development of battery technologies in the context of environmental decision-making and policy (Wang *et al.*, 2023).

Batteries have played an indispensable role in modern society since their invention.

Advancements in battery technology and fast-growing demand for stationary energetic storage are pushing the development of various batteries with diversified applications (Sankaran and Venkatesan, 2022). Leading the revolution of the field, lithium-ion (Li-ion) batteries are now available in many forms, making them suitable for portable electronics, electric vehicles, and stationary storage applications (Khan *et al.*, 2023). On the other hand, conventional lead-acid batteries remain the dominant type being manufactured and deployed for vehicle starting, automotive SLI purposes, and stationary energy storage (Kim and Kim, 2024). Over the years, lead-acid batteries have shown good reliability and durability, particularly when subjected to high surge currents (Kostenko and Zaporozhets, 2024). More recent developments in electrochemical energy storage technologies include the sodium-sulfur (NaS) batteries and flow batteries (Padmanabhan *et al.*, 2024). NaS batteries have a high energy density, long cycle life, and high thermally efficient operating conditions; meanwhile, the components of NaS are typically abundant and low priced, which makes it an attractive option (Sun *et al.*, 2022). Flow batteries could be an economically attractive option, for they can be decoupled in terms of capacity and power and have advantages in terms of flexibility and simplicity of recycling the active materials (Börner *et al.*, 2022). Among various types of flow batteries, the vanadium redox flow batteries (VRB) are considered the most mature and have been commercialized for some stationary applications (Zackrisson *et al.*, 2018; Olabi *et al.*, 2023).

### **Energy efficiency and Carbon footprint**

Electricity storage technologies stabilize the intermittent power generation from renewable sources and, therefore, are essential for the transition to renewable energy systems (Rashid, 2024). Batteries are most suitable for short and medium-term storage, whereas power-to-X systems are better for long-term storage (Tan *et al.*, 2021). Average energy efficiencies and greenhouse gas emissions per stored energy for several electricity storage technologies are therefore explored (Worku, 2022). The electricity storage technologies are then compared with

regard to energy efficiencies and greenhouse gas emissions (Fekete *et al.*, 2023). Since greenhouse gas emissions are related to carbon dioxide (CO<sub>2</sub>) reservoirs, the climate impact from energy storage is considered separately from other environmental properties (Zackrisson *et al.*, 2018). The environmental impact from electricity storage technologies, alternatives to lithium-ion batteries, is also compared (Akinsooto *et al.*, 2024).

Electricity storage can be divided into power and energy, with the former focusing on average power supplied for duration and the latter focusing on stored energy (Zhang *et al.*, 2021). Power-to-X is better for long energy storage as there are no fundamental limitations, although energy efficiencies of 30-50% may be challenging (Battaglia and Vanoli, 2024). However, batteries are more suitable than power-to-X to stabilize renewable power generation on the range of hours to a few days (Onodera *et al.*, 2023). Therefore, power-to-X is excluded (Kilic, 2024).

### **Resource extraction and recycling**

Arguably, the largest problem with producing Lithium-Ion batteries is resource extraction and the associated environmental impact (Tivander, 2016). In many cases, the joint lithium act, which remains in the cells, cannot be recycled and is disposed of in landfills (Gutsch and Leker, 2024). A comprehensive review of the environmental effects of the metals contained in secondary batteries is conducted, with a particular emphasis on those that are more relevant to the technology of lithium-ion batteries (Arshad *et al.*, 2022). Furthermore, efforts in recycling lithium-ion batteries are examined, and their implications for the materials supply chain are discussed (Vera *et al.*, 2023).

Batteries play an important role in the shift from fossil-based to renewable energy; unfortunately, current recycling practices are not sustainable (Baum *et al.*, 2022). Due to a lack of sustainable collection, an economic perspective for recycling has so far not been realized (Ma *et al.*, 2024). An environmentally friendly recycling chain requires recycling processes that, among other

things, prevent the formation of toxic gases, mitigate air pollution, and recover a high percentage of valuable metals (Du *et al.*, 2022). Nevertheless, the rate of recycling for lithium-ion vehicle batteries is low while the market for installed vehicle batteries is in the midst of exponential growth (Harland, 2016).

### **End-of-Life disposal**

The end-of-life disposal of battery technologies is a critically important but often overlooked issue, in which the lifecycle environmental impacts of different battery technologies present very differently (Porzio and Scown, 2021). Disposable primary batteries are generally detrimental to the environment than rechargeable batteries (Crenna *et al.*, 2021). In turn, the end-of-life implications of different rechargeable battery technologies vary even more; both nickel-cadmium and lead-acid batteries are best kept out of landfills, needing to be appropriately recycled due to high toxicity and the potential release of harmful substances like cadmium and lead (Mrozik *et al.*, 2021). End-of-life disposal practices and challenges may soon become more urgent as the gradual replacement of current battery technologies with lithium-ion alternatives leads to batteries that contain potentially explosive materials and capture value-added metals (Chen *et al.*, 2024).

Progressive recycling, or the use of less harmful lithium chemistries, will be key to maintaining the environmental gains of an increasing reliance on batteries (Zhao *et al.*, 2021). But it would require both technological innovations and a redesign of the current consumer market system (Baum *et al.*, 2022). This analysis is framed by current regulations, in particular those of the European Union, China, the United States, and California, as it is primarily through accepted stewardship schemes and large-scale recycling initiatives that such a transition can take place on a general scale (Miao *et al.*, 2022). It is recommended that such schemes be implemented far in advance of the emerging flood of end-of-life batteries (Deshwal *et al.*, 2022). There are billions of batteries used every year around the world (Harland, 2016). Despite the huge number, less than 2% is recycled (Kala

and Mishra, 2021). Most are buried in landfills, risking polluting the earth and water (Shekhar *et al.*, 2022). The rest are incinerated, emitting health-threatening gases and substances (Doose *et al.*, 2021). More than 66,000 tons of batteries containing many hazardous metals such as lead, mercury, and cadmium are distributed in various household appliances (Bird *et al.*, 2022). Most of these batteries end up in municipal solid waste; thus, with a very high probability, they will be incinerated/landfilled (Abdelbaky *et al.*, 2021).

### **Technological advancements and future prospects**

The preferred technology for portable energy storage is the Lithium-ion battery (LIB) with graphite and manganese-based positive electrode (Riaz *et al.*, 2021). Such batteries are now coming up against very real performance limits (Sankaran and Venkatesan, 2022). Replacements are required with high voltage cathodes and aggressive intercalation compounds that possess oxygen atoms and mechanical degradation (Bassyouni *et al.*, 2023). These requirements create significant challenges in terms of the design of the positive electrode responsible for these restraints (Xu *et al.*, 2023). Additionally, there are hazardous conditions posed by the cobalt and the high-voltage lithium cobaltate based cathode materials. The cathode ratio is also likely to reduce the energy density as part of the move to higher voltage and specific energy systems (Zackrisson *et al.*, 2018). This reflects the excitement and challenges ahead in the area of battery technology, discussing recent technological advancements (Hounjet, 2022). At the strategic level, there are materials and the design to be harnessed that could radically alter energy storage capabilities, perhaps prompting all-solid-state systems with the highest specific energies exceeding those of gasoline (Zhang *et al.*, 2024). Simultaneously, there are ongoing commitments at lower-level races for increased lifetime, lowered cost, and improved safety profiles even for well-established systems (Olabi *et al.*, 2023). The collaborative efforts driven by the stakeholders are assessed particularly at the level of industrial-academic partnerships.

Importantly, the disparate likelihoods of various extended battery technologies are discussed, looking past straight technology that is newly considered, such as flow, zinc-air, or liquid metal, may actually be more sustainable, focusing on environmental considerations (Ahmed and Maraz, 2023).

## Policy implications and regulatory frameworks

With rising demand for batteries, policy implications around adoption and associated environmental impacts are increasingly pressing, and more problems and opportunities associated with the adoption of batteries could be identified and addressed (Machín *et al.*, 2024). In light of these considerations, a look at the world of battery production, consumption, and disposal, and examines the relevant international systems regulating each activity (Koniak *et al.*, 2024). There is a brief on the current state of lithium-ion cell production in key jurisdictions and the connections between these practices and efforts to responsibly manage electronic waste (Krishnan and Gopan, 2024). Both the mining and disposal of batteries can have complex, far-reaching effects on air, water, and communities, and it is established that the development of sustainable battery technologies will depend heavily on the synthesis of the many regulations designed to address these impacts (Harland, 2016). From this regulatory landscape, some opportunities to promote the safe, legal disposal of batteries are highlighted, with attention to proposals for the development of shared, standardized systems for tracking the movement of batteries worldwide. Within the policy brief, it is argued that to ensure a sustainable future of transportation and electronics, it will be imperative to adopt and continue refining a stringent international framework that harmonizes practices around the extraction of materials with regulations shaping the collection, dismantling, and disposal of waste (Specker *et al.*, 2024). Sovereign states are asked to collaborate in the development of comprehensive regulations, industries to invest in responsible practices, and consumers to support these efforts by demanding information on the batteries in their products. In this space,

technical guidelines to ensure a minimum level of environmental safety for the end-of-life management of Li-ion cells are proposed that could provide a framework for the harmonized development of international legislation (Ma *et al.*, 2024). In the future, bio-electrochemical systems will be incorporated into improved wastewater treatment processes as part of interdisciplinary efforts to contribute to a greener future and sustainable development (Jadhav and Chendake, 2019).

## CONCLUSION

Lithium-ion batteries have changed the world and continue to improve the way we live, work, and experience the world. Considering the forecast for the expansion of electric vehicle (EV) ownership and the increasing demand for grid stabilization, the principal concerns are how these batteries are used and how much worse the environmental impact might get. Charged LifeCycle Assessment (LCA) modeling and battery literature research reveal lithium-ion batteries may create human and environmental damages ten times worse than lead-acid batteries found in automotive starter batteries, and current lithium-ion battery recycling and second-use regulations are not sufficient to minimize those damages due to the low lifetime value of retired batteries.

Focused industry and government effort might scope that recycle stream in waste legislation; only nickel, cobalt, and copper recyclers might front the cost to comply. Environmental and human health effects of nickel, copper, cobalt, and lithium mining, smelting, and production processes are increasingly well-known as the demand for a more industrially, in the context of battery materials, globalized, and traded economy.

## CONFLICT OF INTEREST

The author declares no conflict of interest.

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