

REVIEW

From Mining to Mobility: Evaluating Environmental Challenges across the Critical Materials Supply Chain for New Energy Vehicles

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ABSTRACT

This review sums up existing information on the environmental issues of critical materials in new energy vehicles (NEVs) on a combined mining to mobility approach. With the increase in the rate of NEV adoption, the environmental cost of operating vehicles will decline as the burden moves to upstream and downstream material life-cycle activities, such as extraction, beneficiation, refining, component manufacturing, use-phase performance, and end-of-life management. We focus on key material categories that provide electrified mobility, such as battery-related material (e.g., Li, Ni, Co, Mn, graphite), high-performance motor-related material (e.g., rare earth elements), conductive and lightweighting material (e.g., Cu and Al). In the supply chain, the prevailing environmental forces consist of high energy requirements and related greenhouse gas emissions, excessive water consumption and water pollution risks, toxicity and human health issues pertaining to chemical inputs and metal discharges, land-use shift, and ecosystem and biodiversity effects. The review notes that there is high regional heterogeneity, which is fueled by ore grades, processing technologies, electricity mixes, and governance capacity, and that when measurements are narrowed to carbon measures, there is a risk of shifting the problem across geographies and categories of impacts. Mitigation pathways are analyzed, such as cleaner extraction and refining, material substitution and dematerialization, battery design, longevity and recyclability, and also the strategies of the circular economy, such as recycling and second-life use. Lastly, we establish research gaps in important areas of supply-chain data disclosure, multi-impact life-cycle assessment approaches, and integrated environmental-social analysis

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to enable sound policy formulation that can be used to achieve sustainable electrified mobility.

Keywords: Critical Materials; New Energy Vehicles; Life Cycle Assessment; Circular Economy; Supply Chain Sustainability

1. Introduction

The world transportation industry is in a radical shift mode that is prompted by the pressing necessity to curb climate change, lower air pollution, and increase energy security. Because road transport is one of the highest sources of greenhouse gas (GHG) emissions globally, the electrification of vehicles has become the pillar of national and global decarbonization efforts^[1,2]. New energy vehicles (NEVs) or battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles are becoming more widely touted as low-carbon options to traditional vehicles based on internal combustion engines. Technological innovation, reduced costs of batteries, and policies have contributed to their fast market penetration. Consequently, the use of NEVs around the globe has grown at a rate never seen before within the last ten years, and this growth is likely to be witnessed in the next several decades^[3].

Although NEVs have great advantages regarding minimizing tailpipe emissions and urban air pollution, their environmental sustainability cannot be considered only in terms of the use-phase performance. An emerging literature has pointed out that the substitution of fossil-fuel-based mobility with electrified transport moves an important portion of environmental costs further up the supply chain, especially to the extraction, processing, and production of materials that are needed to form the vehicle components and energy storage systems. Unlike traditional cars, in which the environmental consequences are influenced mostly by so-called fuel burning during performance, NEVs consume a wide range of essential raw materials, including lithium, cobalt, nickel, rare earth materials, copper, and aluminum. These are the materials underlying batteries, electric motors, power electronics, and lightweight car structures, and their manufacture may require a lot of energy, a lot of land use, and a lot of water and chemicals^[4].

This has become a concern because of the rapidly growing need for critical materials, the security of their supply, and the alteration of the environment. Numerous of these

resources are typified by geographically concentrated resources and production amenities, commonly found in areas having delicate ecosystems, a lack of water, or insufficient government regulation. With decreasing ore grades and the push into more sensitive environmental regions come the mining activities; the environmental footprint that comes with the extraction of raw material is likely to grow. Moreover, downstream processing and refining processes are often based upon energy sources that are carbon-intensive and/or contain dangerous chemicals, and similarly increase life-cycle environmental effects. These issues imply that the sustainability of NEVs will not be limited to clean power production and effective vehicle operation, but also to the environmental outcome of complex global supply chains encompassing the substation of mining sites and final processing systems^[5].

Life cycle assessment (LCA) has emerged as a common method of assessing the environmental impacts of NEVs, and many studies have shown that, in nearly any electricity mix scenario, NEVs are better than conventional vehicles in terms of GHG emissions throughout the lifetime^[6]. Nevertheless, LCA research results usually vary significantly with regard to the system boundaries, data sources, functional units, and placement of assumptions about battery life and recycling. In addition, most of the evaluations pay major concern to climate effects and little concern to other essential environmental aspects, which include water utilization, toxicity, land-use change, and biodiversity decline. Subsequently, the macro environmental impacts of the massive deployment of NEVs are not fully comprehended, especially in relation to material supply chains that cut across more regions and have various production technologies^[7].

Critical materials have therefore also become a novel sustainability bottleneck in the shift to low-carbon mobility. These materials have significantly different environmental impact profiles at the life-cycle stages, in addition to their economic and geopolitical importance. An example is that the extraction of lithium in the brine systems requires a lot of water consumption in the arid areas, and the mining of

cobalt and nickel may produce high levels of toxic emissions and tailings. Production of rare earth elements, required in high-performance electric motors, can cause deplorable land disturbances and permanent contamination threats. Simultaneously, the technological innovation is also transforming the patterns of material demand at an extremely fast pace by creating alternative battery chemistry, higher energy densities, and strategies of material substitution. These dynamics add more uncertainty to the future environmental situation and make it more difficult to create strong sustainability policies^[8–10].

In this regard, an integrative and holistic revision of environmental issues in the whole critical materials supply chain of NEVs is urgently required. The available literature tends to be disjointed, with the research concentrating on single materials, certain stages of the life-cycle, or independent environmental indicators. There is a paucity of reviews that combine mining, processing, and manufacturing, use, and end-of-life stages into a single analytic platform. In addition, the relations between the technological trajectories, the material demand, environmental effects, and policy interventions are under-researched. It is critical to address these gaps to discover environmental hotspots, forecast trade-offs, and direct policies that can match climate goals with sustainability goals in general.

The purpose of this review is to assess environmental issues linked to critical materials in NEVs on an integrated or ore-to-mobility basis. The analysis scope covers the entire life cycle of materials, which includes the extraction, processing, and refining of the raw material, the making of components and vehicle products, the use phase of the material performance, and the end-of-life management possibilities such as recycling and reuse. Several dimensions are looked upon in the environment, which are energy usage, greenhouse gas emissions, water usage and pollution, land usage, ecosystems, and toxicity risks. The synthesis of the results of life-cycle assessments, empirical case studies, and policy research aims to give a comprehensive perspective of the distribution of environmental burdens along the NEV materials supply chain through the review^[11–13].

Besides the identification of environmental impacts, this article pays some special attention to the mitigation strategies and policy implications. The technological development

of low-impact mining methods, more open processing paths, and better battery designs is incredibly promising to minimize pressure on the environment. Simultaneously, the idea of a circular economy, material recovery, recycling, and second-life use of batteries, is becoming widely accepted as an important direction to increase resource efficiency and minimize the need to demand primary materials. Policy tools, such as environmental regulations and sustainability guidelines, long-life-cycle producer responsibility programs, and supply chain transparency programs, are at the core of influencing the environmental performance of NEV material systems. The interaction of these measures and the points of trade-offs is an important aspect of the governance of the mobility transition^[14].

These goals have been echoed in the structure of this review. Section 2 of this paper, after this introduction, gives an overview of critical materials employed in NEVs, including the classification of materials, their material intensity, and supply chain properties. Section 3 follows the life cycle of NEV materials from mining to waste disposal, with major process and system interactions being identified. Section 4 summarizes evidence regarding environmental effects at life-cycle stages, outlines key hotspots, and areas of uncertainty. Section 5 explains mitigation measures and policy response, which is based on technological, circular, and governance-based solutions. Section 6 identifies the main gaps and directions of research in the future, showing the necessity of integrated, dynamic, and multi-dimensional sustainability assessments. Last but not least, Section 7 is a conclusion where the key findings are summarized, and strategies towards environmentally responsible NEV development are outlined^[15–17].

This review makes a valuable addition to the existing knowledge of environmental issues surrounding the material base of new energy vehicles by providing a critical and thorough synthesis of existing knowledge. It intends to assist the researchers, policymakers, and industry stakeholders in the development of mobility transitions that are not only low-carbon but are also resource-efficient and environmentally sustainable in global supply chains. **Figure 1** shows the combined mining to mobility framework embraced in this review to reflect the life-cycle processes that are closely interlinked, and the relationship that is in a form of feedback^[18].

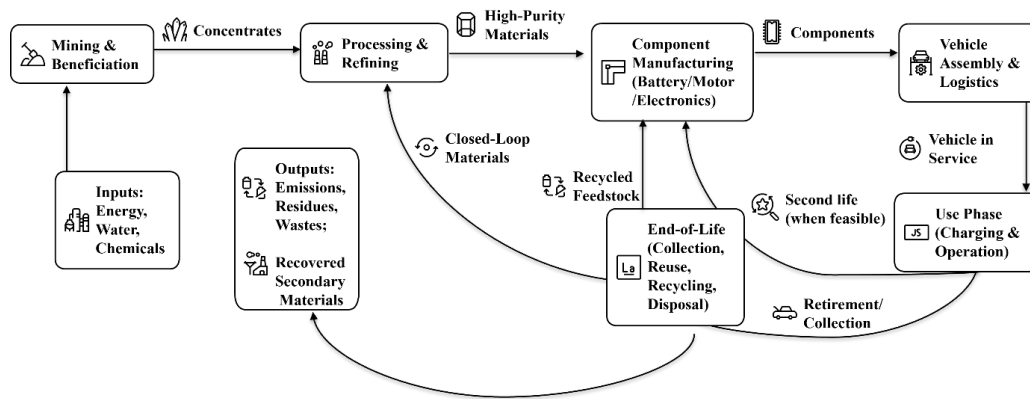


Figure 1. Conceptual framework of the critical materials supply chain for new energy vehicles, illustrating material flows from mining to mobility and circular feedback loops.

2. Critical Materials for New Energy Vehicles

The high-volume implementation of new energy vehicles is essentially made possible through a range of materials that are significantly different from those employed in traditional internal combustion engine cars. Whereas classic vehicles use a large percentage of steel as well as cast iron and comparatively limited percentages of non-ferrous metals, NEVs are marked by a greatly increased reliance on electrochemically active elements, high-purity metals, and functional materials with particular magnetic, electrical, and thermal characteristics. These materials are usually known as critical materials, and they are simply said to be critical due to their significance to important technologies as well as the risks that they might have on the supply, the environmental effects, and the long-term availability. The fact that the kinds of critical materials employed in NEVs and their technological application, as well as the characteristics of their supply chain, are understood, is the precondition to evaluating the environmental issues addressed in further sections^[19].

2.1. Definition and Scope of Critical Materials in the Context of NEVs

Critical materials have developed and have a different meaning in policy, industrial, and academic realms. Overall, a material that has a high economic or technological value, as well as a high threat of supply disruption, is considered a critical one. The meaning of criticality with regards to NEVs transcends the economic factor to the environmental and

sustainability factor, because mining and refining of most of these materials is linked with substantial ecological costs^[20].

The essential materials used in NEVs can be loosely defined as materials that are necessary in batteries, electric drives, power electronics, and lightweight vehicle structures, and whose replacement is difficult to implement technically or expensive in the short to medium term. There are two important characteristics of this definition. To begin with, the core components have critical materials that define the performance, efficiency, and safety of the vehicles. Second, they are commonly dependent on multifaceted, globally dispersed supply chains that are vulnerable to geopolitical, regulatory, and ecological limitations. With the rapid expansion of NEV implementation, the need for these materials grows swiftly, which increases the threat to the supply and environmental pressure^[21].

2.2. Classification of Critical Materials Used in New Energy Vehicles

Functionally speaking, the critical materials applied in NEVs can be divided into a few major categories based on their presence in the vehicle system^[22]. The most notable and the most discussed category is represented by battery-related materials because the process of electrochemical energy storage is core to the operation of NEV. Most commercial lithium-ion batteries use lithium, cobalt, nickel, and manganese, and various new technologies could add silicon, sulfur, or solid electrolytes. They must be supplied in high purity and definite forms, which makes their processing very intensive on the environment^[20].

A second important major category of material use

is electric motors and power electronics. The use of rare earth elements, including neodymium, praseodymium, dysprosium, and terbium to make high-performance permanent magnet motors has made them powerful and efficient in density with low energy sources. Inverters and converters, which are part of power electronics, rely on conductive and semiconductor materials, and are based on copper, aluminum, silver, and even widening bandgap materials. Whereas possible alternative motor designs may deem to cut or do away with rare earth elements, they are still predominant in most NEV platforms today, with their higher performance attributes^[23].

A third group is the structural and lightweighting materi-

als which are indirectly related to the efficiency of the vehicles. The mass of vehicles is reduced by using aluminum and high-strength steels of the advanced type, and copper is essential in electrical systems and thermal control systems. These materials are not specific to NEVs, but they are used more per vehicle than conventional vehicles, especially when it comes to copper and aluminum. The mixture of these categories of materials shows that NEVs are not only energy-consuming products, but also extremely material-consuming systems^[24–27]. The material requirement is highly technology-driven, as seen in **Table 1**, especially battery chemistries and permanent magnet motor designs.

Table 1. Critical materials used in new energy vehicles and their main applications.

Material	Primary Application in NEVs	Functional Role	Technology Dependency
Lithium	Battery (electrolyte, cathode)	Energy storage, ion transport	High (battery chemistry)
Cobalt	Battery cathodes	Thermal stability, cycle life	Medium–high
Nickel	Battery cathodes	Energy density enhancement	High
Manganese	Battery cathodes	Structural stability, cost reduction	Medium
Graphite	Battery anodes	Lithium intercalation	High
Rare earth elements (Nd, Pr, Dy)	Electric motors	Permanent magnet performance	High
Copper	Wiring, motors, electronics	Electrical conductivity	High
Aluminum	Vehicle body, battery casing	Lightweighting, thermal management	Medium

2.3. Material Intensity and Technology Dependency

Technological decisions, especially battery chemistry, vehicle size, and drive shaft, have a strong influence on the amount and makeup of the amount of critical materials in NEVs. Various chemistries of batteries have different material intensity profiles. The nickel-based lithium-ion batteries have a higher energy density but demand more nickel and cobalt; the lithium iron phosphate batteries do not need as much cobalt and nickel, but have lower energy density. The trade-offs do not necessarily affect the performance of the vehicles or the cost, but also the environmental impacts of the upstream activities of mining and processing^[28,29]. **Figure 2** presents the schematic distribution of the critical materials across the main vehicle components with particular attention to the intensity of the materials of batteries, motors, and power electronics.

The material intensity is also associated with the vehicle design and use. Four to twelve-wheeled models that have a longer range tend to have effects of larger battery packs that consequently consume more of the vital material. In the same way, the use of all-wheel drive systems or

high-performance motors may raise the consumption of rare earth elements and copper. With the growth of NEV markets into a wide range of markets and using heavy-duty vehicles and commercial fleets as an example, the material demand trends will be more diversified, making it more challenging to anticipate which changes will occur in the environment in the future.

Technological innovation serves two aspects in determining material intensity. On the one hand, the energy density, manufacturing efficiency, and system integration may decrease the quantity of material per unit of vehicle performance. Conversely, the increase in the volume of vehicle production can be faster than the efficiency improvement, and the total effect will be a rise in the absolute material demand. These dynamic highlights the significance of measuring the material usage on the per-vehicle, as well as on the system level^[30].

2.4. Supply Chain Structure and Geographic Concentration

The supply networks of important materials for NEVs are very internationalized and geographically concentrated,

and this aspect has significant consequences on the distribution of environmental burden^[31]. Due to the conducive geological factors and the lack of capacity to govern the environment, mining activities are frequently situated in areas with good geology, whereas processing and refining are

more often based in fewer industrial centers. Such physical distance between the extraction of resources, processing of materials, and manufacturing of vehicles may blur the environmental issues that are linked to NEVs by end users and policymakers in areas of consumption.

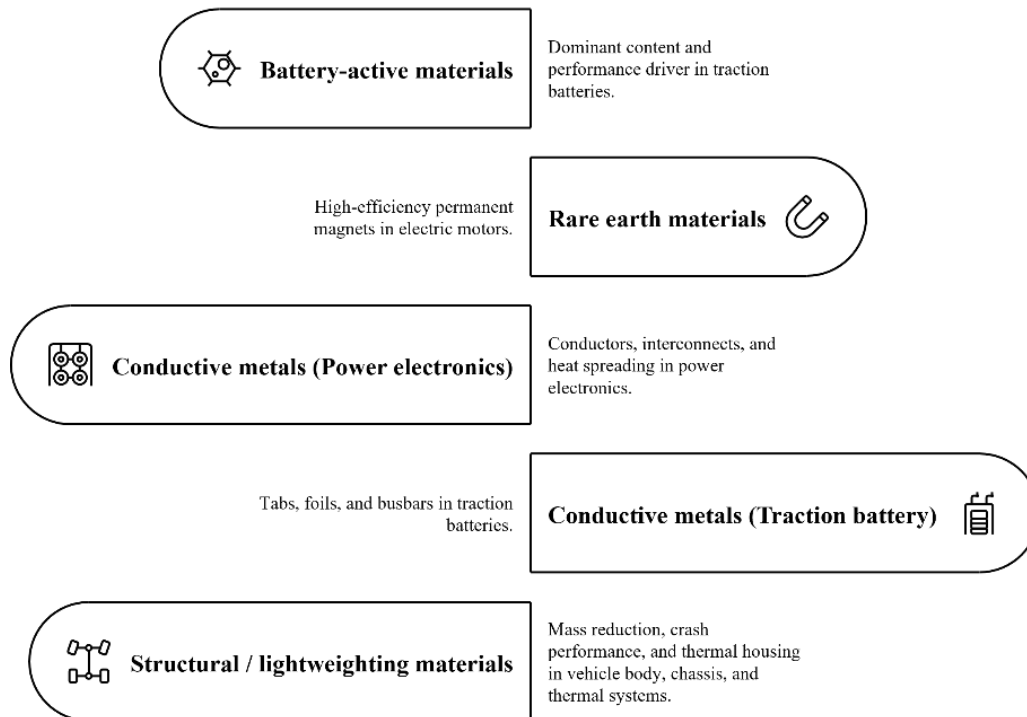


Figure 2. Distribution of critical materials across major new energy vehicle components and functional subsystems.

Geographic concentration also makes the supply disruption more vulnerable and may emphasize environmental pressures in certain areas. An example of this is that the control of a few countries in the production or refining of some materials can result in the quick expansion of the extraction processes before adequate time to establish the best environmental management systems is fully attained. With the demand for NEVs persisting to increase, these areas can suffer cumulative environmental consequences that are not limited to single mining sites, such as water shortage, land degradation, and permanent contamination. On an environmental front, the worldwide system of NEV material supply chain casts doubt on the subject of responsibility and accountability. The externalization of environmental effects is often transferred to upstream areas, and the advantages of vehicle electrification are mostly concentrated in downstream markets. This asymmetry creates the necessity to evaluate matters transboundary ecologically, and policy models that

consider transboundary environmental impacts^[12].

2.5. Environmental Dimensions of Material Criticality

The conventional approaches of measuring material criticality have been mainly based on the economic value and risk to supply, and do not usually take into account the environmental performance. Nonetheless, in the case of NEVs, the environmental dimensions are increasingly being viewed as a part and parcel of criticality. The relatively abundant resources still can create serious sustainability issues if they are extracted and processed in such a way that the process causes high energy use, greenhouse emissions, or serious ecological damage. On the other hand, materials that have a greater risk of supply could have a relatively lower environmental impact per unit of use.

By incorporating environmental pointers into criticality measurements, one can have a more refined perception of

sustainability trade-offs. This practice can be used to detail materials that are environmental hotspots in the NEV life cycle and give them a priority in either technological innovation, substitution, or improved recycling. Simultaneously, it demonstrates that modern knowledge has its gaps because, in most cases, environmental information on numerous important materials has not been fully developed, is not consistent, or is extremely context-specific^[32].

To conclude, new energy vehicles are material-demanding on critical materials, which makes the connection between the technological performance, the environmental sustainability, and supply security. The deployment of NEVs faces the environmental issues of their classification, material intensity, and supply chain nature. A comprehensive analysis of such materials gives the basis for the life-cycle analysis introduced in the next section, which follows their routes starting with ore mining to end-of-life management.

3. Life Cycle of Materials for New Energy Vehicles: From the Ore to the Waste

The life cycle of materials, on which new energy vehicles rely, is inherently tied to the environmental impact of new energy vehicles. In contrast to traditional cars, the major impacts of NEVs are distributed upstream and downstream of material supply chains, unlike the dominance of fuel combustion in the use stage of conventional cars. A life-cycle approach is thus required in order to describe the entire spectrum of processes by which critical materials are mined, refined, used, and finally repurposed or recycled. Following this part, the material life cycle of NEVs is followed, starting with the extraction of primary resources and up to the end-of-life of NEVs, indicating the most important processes, technological avenues, and interactions of the system that determine the environmental performance^[11].

3.1. Raw Material Extraction and Beneficiation

The NEV materials life cycle starts with the extraction of the raw materials from the crust of the earth, the phase that is sometimes related to the most immediate and localized environmental perturbation. Most of the materials used in manufacturing NEVs are mined by using diverse min-

ing methods, such as the open-pit and underground mining of hard-rock ores, solution mining, and evaporation of the brine-based materials. The extraction method selected is determined by geological factors, grade of ore, and economic factors, although it poses an important implication to the use of energy, land disturbance, and water.

The pattern is that lower-grade ores or more distant and environmentally sensitive areas are exploited as the easier and higher-grade deposits are depleted, mining activities are driven away to lower-grade ores or more remote and sensitive areas. This tendency translates into an increase in the material throughput/unit of useful metal, energy necessities, as well as waste production during extraction and beneficiation. Valuable minerals are concentrated through beneficiation processes, crushing, grinding, and flotation, which produce voluminous amounts of tailings, which would need to be managed over a long period. Such tailings usually have the leftover metals and processing chemicals, which can be hazardous in the event of soil and water pollution unless managed well^[33].

Moreover, numerous essential materials of NEVs are also by-products of other mining, without being the main ones. The co-production makes supply chains more complex and decouples the availability of materials from the demands of NEV, besides complicating the process of assigning environmental effects to particular materials. Consequently, the environmental footprint of the extraction of raw materials to produce NEVs is very context dependent and depends on both geological and institutional factors.

3.2. Processing, Refining, and Materials Production

Raw materials after extraction are processed and refined through a process to obtain purity and chemical forms needed in the application of NEV. These processes tend to be highly energy-demanding and technologically more intricate than the extraction process itself and may represent a significant portion of the environmental costs of the life-cycle. There are many different processing routes with different materials, but the most common ones include pyrometallurgical and hydrometallurgical, and a combination of both^[34].

The pyrometallurgical processes are based on the operation of high-temperature treatments to separate and purify metals, and are very energy-consuming and produce green-

house gases, especially where fossil fuels are predominant in supplying energy. Processes based on aqueous chemistry, such as hydrometallurgical processes, can be more selective and can have lower energy intensity, but they can involve high amounts of acid, solvents, and other reagents. These chemicals present other environmental and occupational health risks with regard to their handling, disposal, or recycling.

The production of materials also generates several wastes such as slags, residues, and effluents, which have to be taken care of in order to avoid environmental harm in the long run. Availability of clean energy, regulatory standards, and technological maturity are important factors that affect the environmental performance of this stage. Since the spatial concentration of processing and refining is necessarily limited geographically, environmental loads at this point are not evenly distributed through the world supply chain^[35].

3.3. Component and Vehicle Manufacturing

After the refined materials have been produced, they are then converted into components and assembled into vehicles through very specialized and capital-intensive manufacturing processes. In the case of NEVs, battery production is one of the most significant processes because it encompasses several energy- and material-intensive processes such as electrode manufacture, cell assembly, formation cycle, and pack assembly. Controlled environments and accurate control of quality are common in these processes, which add to high electricity demands and indirect emissions. Additional complexity in materials is made by the manufacturing of electric motors, power electronics, and auxiliary systems on top of batteries. Another process that may result in waste and emission of hazards is the process used in the fabrication of permanent magnets, where there are extra steps in the process. On the same note, the high usage of copper and aluminum in wiring, thermal management, and structural constituents also raises material throughput, as well as energy usage in the manufacturing process^[12,30].

The supply chains of NEVs are frequently located all over the world, with parts manufactured in other parts of the world and then assembled to create a final vehicle. Transportation and logistics, hence, add to the environmental effects, especially when the components are moved to faraway

places. These effects are generally smaller than effects related to material extraction and processing, but they increase in importance with the increase in production volumes.

3.4. Use Phase and Material Performance over Time

At the stage of use, NEVs have embedded materials that serve their purposes for long periods, but are not environmentally neutral. The degradation of the battery, fatigue of materials, and the wear of components affect the efficiency and the maintenance needs of the vehicle, as well as the rate of replacement. In particular with batteries, degradation throughout life could influence the range of vehicles and require early change, thus adding cumulative material demand. Material-energy system interactions also determine the environmental consequences of the use phase. The generation of electricity used to charge vehicles defines which indirect emissions will be created when using a vehicle, and the increase in the number of charging stations presents new material and land-use challenges. These effects are frequently discussed independently of vehicle materials, but these effects are tightly connected with one another due to the interactions on the system level^[36,37].

Regarding the life-cycle view, the use phase will be the link between upstream material investments and downstream end-of-life results. When making decisions involving battery management, maintenance practices, and vehicle lifespan, it can be observed that the timing and magnitude of material flows into waste management systems can be influential.

3.5. End-of-Life Management and Circular Pathways

The last process in the material life cycle is the management of the NEVs and their components at the expiry of service. Vehicles have been traditionally dismantled, shredded, and some parts of them are also recycled, and metals like steel and aluminum are recycled at relatively high rates. With NEVs, however, the end-of-life management is more complicated as there are high-energy batteries as well as the variability of material compositions. Battery end-of-life channels are disposal, recycling, and second life use, like stationary energy storage^[38]. Recycling technologies are also aimed at collecting useful metals and lessening primary

mining, although their impact on the environment is not uniform due to the design of the process, energy consumption, and recovery rates. Recycling of NEV batteries remains an unfinished system in most areas, and it is unclear how much of the material will be recovered shortly^[39].

Strategies of the circular economy attempt to fulfill material loops that require the prolongation of the product life, enhance recyclability, and use secondary materials in the new production cycles. Although these approaches have a lot of

potential in terms of their ability to lower the environmental pressure, they also have technical, economic, and regulatory challenges. Circular pathways require a combined effort on the supply chain, including product design and materials selection, collection systems, and market incentives. To be more precise, **Table 2** gives a summary of the key life-cycle phases of critical materials in new energy vehicles, associating the prevailing processes with the primary environmental issues throughout the ore-to-waste system^[11].

Table 2. Life-cycle stages of critical materials for new energy vehicles.

Life-Cycle Stage	Main Processes	Typical Outputs	Key Environmental Concerns
Raw material extraction	Mining, beneficiation	Concentrated ores	Land disturbance, water use
Processing & refining	Pyro-/hydrometallurgy	High-purity metals	Energy use, emissions, waste
Component manufacturing	Battery, motor, electronics fabrication	Functional components	Electricity demand, chemicals
Vehicle integration	Assembly, logistics	Finished NEVs	Transport-related emissions
Use phase	Operation, maintenance	Mobility services	Indirect emissions (electricity)
End-of-life	Recycling, reuse, disposal	Secondary materials, waste	Recovery efficiency, pollution

To conclude, the life cycle of new energy vehicle materials is a complicated chain of interdependent steps, each of which has a positive effect on the overall environmental performance. The impacts are not equally spread throughout extraction, processing, manufacturing, use, and end-of-life stages and are influenced by technological decisions, geographical setting, and system of governance. The knowledge of this life-cycle dynamics forms the basis of the analysis of the environmental impact that will be given in the next section, which summarizes the evidence concerning how material flows between mining and mobility can be converted into various environmental problems.

4. Environmental Impacts of Materials from Mining to Mobility

NIVEA The lifecycle of the critical materials in new energy vehicles is linked to diverse sets of environmental effects that go well beyond the use of the vehicles. Although electrification can significantly decrease or eliminate the tailpipe emissions, the upstream and downstream processes of material supply chains proceed with new environmental demands, which are both geographically remote to end users and less visible in mass communication. The effects are multidimensional; they include climate, water resources, ecosystems, and human health. To gain a comprehensive insight into these environmental issues necessitates a com-

bined assessment that reflects the flow of materials from mining to mobility into cumulative as well as interactive effects throughout the life cycle^[11,40,41].

4.1. Energy Consumption and Resource Depletion

The use of energy is a prevailing cause of environmental effects throughout the NEV material life cycle. Extraction and treatment of important materials are also energy-intensive in nature, especially as the decreasing ore grades require the transportation and treatment of more material to produce the same quantity of available metal. Comminution, separation, and refining need a lot of mechanical and thermal energy, which may be provided by fossil fuels in areas where renewable energy penetration is less pronounced^[40].

The depletion of resources is directly related to the utilization of energy since deposits with lower grade and a more complex nature require a higher intensity of material throughput and processing. Even though geologically, most of the critical materials are not scarce, in terms of economic recoveries, avenues are limited by technology and environmental conditions. The fast growth of NEV production leads to pressure on these reserves, which raises the problem of availability in the long term and the impact of developing extraction in more marginal or environmentally sensitive lands. The depletion of resources is not purely a physical scarcity issue as viewed in a life-cycle perspective, but also

of rising costs in environmental terms to access the available resources^[42].

System efficiency gains in the use and processing of materials can partly contribute to these trends, although they are frequently set back by increases in aggregate demand. Consequently, the amount of energy used and resources extracted due to NEVs is likely to increase in absolute amounts, but per-unit effects decrease.

4.2. Greenhouse Gas Emissions across the Material Life Cycle

One of the most widely researched dimensions of environmental aspects of NEVs is greenhouse gas emissions; nevertheless, their allocation throughout the material life cycle shows significant trade-offs^[43]. Although the use stage of NEVs generally has much lower emissions compared to those of conventional vehicles, especially in the area of low-carbon electricity, the upstream emissions related to the production of materials can be high. One of the biggest portions of the embedded carbon footprint of NEVs can be attributed to mining, refining, and manufacturing stages, with battery production becoming one of the most emission-intensive processes.

The intensity of the greenhouse gas emissions of the life-cycle is diverse in terms of the regional energy mixes, technology routes, and efficiency of production. Processed materials in areas with electricity grids of high carbon content have a higher embodied emission level, which is imported by the vehicle manufacturing and consumption areas. This is a spatial decoupling of the production and consumption of emissions, and makes it difficult to evaluate and control the actual climate effects of NEVs. Comparative analyses have revealed that when compared to internal combustion engine vehicles, NEVs tend to produce net greenhouse gas reductions over their lifetime, although they have greater manufacturing emissions. Nonetheless, the level of those cuts is based on assumptions about the car's life, replacement of batteries, and recycling. This means that ensuring that the production sources of upstream emissions are less polluting, by using cleaner energy sources and more efficient processes, is important to maximize the climate benefits of electrified mobility^[37,44].

4.3. Water Use and Aquatic Environmental Impacts

The water usage and environmental effects on water are especially sensitive to some of the most essential materials in NEVs. Mining and processing activities normally consume a lot of water in extracting the ore, processing the mined mineral, cooling, and managing wastes. In water-intensive areas, these needs may make the use of water in the industrial, agricultural, and household sectors more competitive, which causes both social and ecological pressure. In addition to the consumption of water, water pollution is a great threat to the environment. Mining and processing effluents can contain acids, heavy metals, and other contaminants, which can reduce the quality of surface and underground waters. Tailings storage facilities are long-term sources of possible contamination, particularly during failure or poor management. These may have lasting effects for decades on the ecology of the area and the human populace, even after the mining operations have been abandoned^[11,45,46].

The NEV materials water footprint is very contextual, and it is determined by the local hydrology, extraction technologies, and regulatory structures. With the increasing NEV material requirement, the effects of water will potentially increase in some areas, highlighting the necessity of assessing them on a case-by-case basis and addressing their water sensitivities using management plans.

4.4. Toxicity and Human Health Implications

Another important aspect of environmental concern in the supply chain of NEV material is related to toxicity impacts. The mining and refining of numerous important resources deal with the contact of dangerous materials, such as heavy metals, acids, and organic solvents. These are dangerous to the workers at the mining and manufacturing premises and to the communities around due to emissions of carbon monoxide in the air, water pollution, and soil erosion. The effects of the environment on human health can be both directly by occupation and indirectly by environmental pathways, which influence food and water systems. In other places, these risks are not properly regulated and enforced, which contributes to an unequal burden on vulnerable groups. In terms of life-cycle assessment, the measurement of toxicity

effects is still complicated because of the scarcity of information, complicated routes of exposure, and ambiguity in the dose-response relation^[12,47].

Regardless of these difficulties, it has been indicated that some materials and processes can experience toxicity-related effects that are as severe or worse than climate-related effects. Toxicity must be tackled thus with specific interventions which may involve better process controls, replacement of the hazardous chemicals, and better regulatory supervision.

4.5. Land Use Change, Biodiversity Loss, and Ecosystem Degradation

The effects of material extraction of NEVs on land use and the ecosystem are among the most obvious and irreversible. Large-scale land disturbance, which includes vegetation clearing, soil erosion, and fragmentation of the landscape, is often a part of the mining activities. Such alterations may result in the loss of habitat and loss of biodiversity, especially in areas with high ecological potential or low resilience. Besides direct occupation of land, there are also indirect effects like the construction of infrastructure, waste disposal, and the enhancement of human use, which may further ruin ecosystems. The environmental damages caused by various mining projects in an area can be beyond the ability of the immediate surroundings to repair, and cause ecological destruction over time. These effects cannot be easily measured and are frequently not reflected in life-cycle analyses because of methodological issues and lack of data^[48,49].

Under sustainability, issues of land use and biodiversity have a problem with the idea that NEVs are unquestionably green technologies. They emphasize the necessity to focus on the need to take into account not only global indicators of the environment, e.g., greenhouse gas emissions, but also the local and long-term ecological impact of material supply chains.

4.6. Integrated Environmental Trade-Offs and System-Level Implications

Environmental effects of NEV materials do not exist in transit, but they interact at different stages of the life cycle

and on the environmental planes. The attempts to cut down greenhouse gas emissions may also raise water utilization or toxicity in case they are based on more resource-requiring materials or procedures. On the same note, the ways of reducing the depletion of resources with increased recycling can bring new energy or chemical requirements. These trade-offs highlight the need to have integrated, system-level evaluations that go beyond individual indicator evaluations. An integrated perspective of the environmental effects of mining on mobility is needed to discover the real sustainability benefits and prevent relocation of problems across geographical regions, life-cycle, or environmental labels^[11].

While decarbonization is a primary driver of the transition toward new energy vehicles, strategies focused solely on reducing greenhouse gas emissions may unintentionally intensify other environmental pressures. For example, the expansion of lithium brine extraction in arid regions may exacerbate water scarcity, while large-scale mining of nickel, cobalt, and rare earth elements can lead to land disturbance, habitat fragmentation, and biodiversity loss. These dynamics illustrate the risk of environmental problem shifting, whereby climate mitigation benefits are achieved at the expense of local ecosystems or water resources. Therefore, evaluating NEV sustainability requires integrated, multi-impact assessments that simultaneously consider climate, water, land, and toxicity dimensions across the entire supply chain.

To sum up, the environmental effects of new energy vehicle critical materials are complex and unevenly dispersed on global supply chains. Although the benefits of NEVs are obvious in the context of lowering operational emissions, the material basis of this technology brings up new categories of environmental issues that need to be thoroughly discussed in order to make the transition to mobility even more sustainable. Below this analysis, the following section expands on the analysis by analyzing mitigation strategies and policy implications that would help to minimize the environmental burden whilst preserving the technological and societal advantages of NEVs^[11,50]. **Table 3** synthesizes the analysis of the distribution of environmental impact hotspots throughout life-cycle stages, and it demonstrates how various material-related pressures are created during extraction to end-of-life management.

Table 3. Environmental impacts associated with NEV materials across the life cycle.

Environmental Impact Category	Most Affected Life-Cycle Stages	Primary Drivers
Energy consumption	Extraction, refining, manufacturing	Ore grades, process intensity
Greenhouse gas emissions	Refining, battery production	Fossil-based electricity
Water use	Mining, processing	Brine extraction, chemical processing
Toxicity & human health	Mining, refining, recycling	Heavy metals, solvents
Land use & biodiversity	Mining	Habitat loss, landscape alteration
Waste generation	Processing, end-of-life	Tailings, slags, residues

5. Mitigation Strategies and Policy Implications

A coordinated effort on the technological, economic, and institutional levels is required to address the environmental issues related to the use of critical materials in new energy vehicles^[51]. Since the environmental effects are present at various points in the material life cycle and are spread throughout global supply chains, the mitigation strategies need to be more than isolated technological solutions and need to address system-level interactions. Meanwhile, policy frameworks are quite essential in the formulation of incentives, technological orientation, and the internalization of environmental externalities. This section explores the major mitigation measures and policy ramifications with respect to technological innovation, circular economy solutions, and governance systems that can all decrease the environmental impacts of mining on mobility^[52–54].

5.1. Technological Innovation along the Material Supply Chain

The first way of reducing the environmental impact of the NEV materials is through technological innovation. At the upstream level, mining technologies can decrease the energy, water, and land disturbance. Examples are better ore-sorting algorithms, in-situ recovery, using computerized monitoring to optimize resource recovery and reduce wastes. These inventions can be improved to increase material recovery and decrease the environmental impact of mining activities, especially in areas with regulatory or resource limitations. Cleaner production technologies can reduce greenhouse gas emissions and releases of pollutants significantly in the processing and refining process^[55]. Carbon intensity of material production can be minimized by the adoption of low-carbon energy sources, process electrification, and enhanced thermal efficiency. Simultaneously, the toxicity-related effects can be alleviated by the creation of

alternative processing pathways that will utilize fewer toxic substances or produce fewer byproducts. Nonetheless, implementation of such technologies can be associated with high capital investment and favorable policy conditions to break the economic and institutional barriers^[56,57].

At the downstream, the battery and component design can be used to decrease the intensity of materials, without any loss of performance. An increase in energy density, durability, and manufacturing efficiency will reduce the unit vehicle’s critical materials. Besides that, another line of research, in alternative battery chemistries and motor designs, acts to eliminate dependence on especially problematic materials. As much as these replacements can help mitigate certain environmental stressors, some new factors of trade-off can be added, prompting the necessity of undertaking a thorough life-cycle analysis of new technologies.

5.2. Circular Economy Strategies for Critical Materials

Circular economy solutions are becoming part of the wider set of strategies that are necessary to reduce the environmental footprint of NEV material supply chains. Circular strategies will help in solving environmental and supply security issues by increasing the lifespan of products, improving the cost-efficiency of materials, and preventing overreliance on the main resources. Batteries are a center of circularity with respect to NEVs because they are expensive to purchase materials, and their service life is comparatively low compared to that of the vehicle^[58].

Recycling technologies strive to extract useful metals from end-of-life batteries and components and minimize the necessity of new mining and refining. Each of the recycling processes discussed in this paper will have a different environmental profile based on the energy needs and recovery efficiencies, as well as chemical consumption, in mechanical, pyrometallurgical, and hydrometallurgical recycling. Increasing recycling capacity and enhancing the performance

of the processes are the keys to achieving environmental impact. Especially with the ever-increasing quantities of batteries approaching end-of-life in the next several decades, it will be necessary to increase recycling and optimize the process^[59,60].

In addition to recycling, reusing, and second-life applications, can provide other solutions to enhance efficiency in resources. The batteries, which no longer serve the purpose of vehicle performance, can be used in stationary energy storage or other purposes; the useful life of such a battery is extended, and it puts off waste streams. Nevertheless, the environmental benefits of second-life applications are subject to other variables, including transportation increment, recycling of the energy, and ultimate recycling. To ensure the greatest possible benefits for the environment, the application of the principles of the circular economy to the design of products, modularity, and ease of disassembly is thus necessary.

5.3. Policy Instruments and Governance Mechanisms

The policy interventions are decisive and accelerating the mitigation strategies throughout the NEV material supply chain. The environmental regulations in mining, processing, and manufacturing are able to set minimum performance levels and curb damaging practices. These regulations are especially crucial in the upstream areas where the environmental

regulation might be less effective and the effects more critical. Nonetheless, the imbalance of regulatory systems among nations may result in an environmental burden shifting, instead of absolute decreases. One of the most important policy mechanisms to enhance the concept of circularity is the extended producer responsibility schemes. These schemes provide incentives for design improvement and material recovery, as well as the development of recycling infrastructure by placing the responsibility of end-of-life management on manufacturers or importers. Regarding NEVs, producer responsibility policies can assist in ensuring that the waste disposal of batteries and components takes place in an environmentally responsible way, as well as assist in developing the markets of secondary materials^[12].

Supply chain transparency and traceability programs are currently under the spotlight as a way of dealing with environmental and social risks related to critical materials. Environmental disclosure requirements, certification schemes, and due diligence obligations can enhance accountability and allow consumers and regulators to make better-informed decisions. Nevertheless, effective traceability systems on complex and globalized supply chains are still a major challenge, especially of materials that are produced under the co-production or informal mining processes^[61,62].

Figure 3 integrates technological, circular, and governance-based mitigation pathways and illustrates their interactions across life-cycle stages.

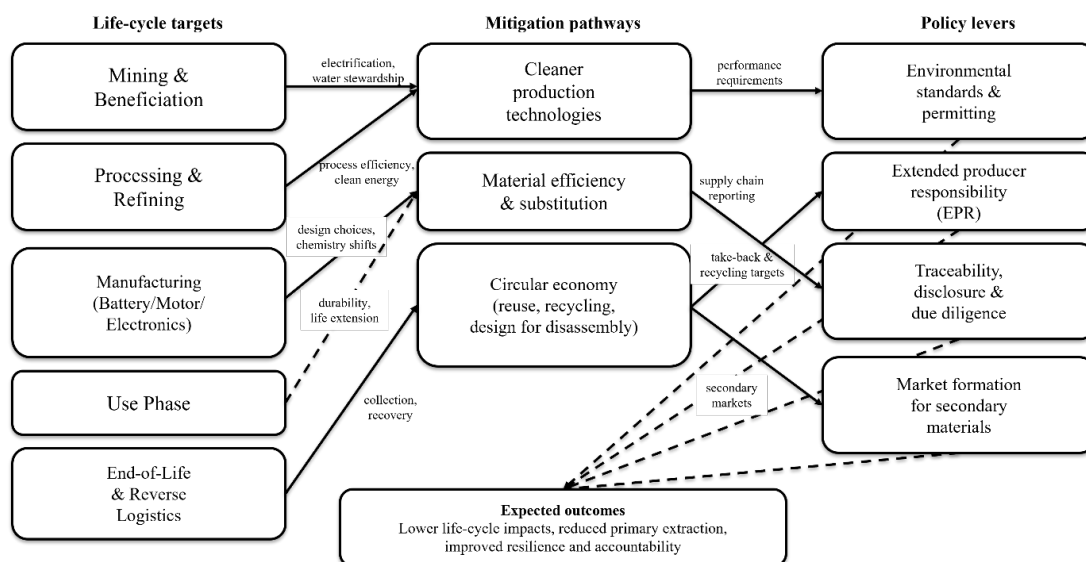


Figure 3. Mitigation pathways and policy levers for improving the environmental sustainability of new energy vehicle material supply chains.

5.4. System-Level Trade-Offs and Policy Coordination

NEV materials mitigation strategies will always come with a trade-off between the environmental goals, economic, and social aspects. To illustrate, mining with elevated environmental requirements can raise the cost of production and material availability, and fast-growing recycling infrastructure can demand high energy and resource utilization in the near future^[63]. These trade-offs have one way in which it is necessary to balance the policy approach to coordinate environmental, industrial, and climatic goals. Inter-country

collaboration is especially significant due to the fact that NEV material supply chains are bound across borders. The policy adopted in vehicle-consuming areas may have a ripple effect on the producing areas as well as the decisions made on investment, environmental activities, and the developmental outcomes in the areas. The negative externalities can be reduced through coordinated standards, information sharing, and the transfer of technology to assist in achieving sustainable development objectives^[64,65]. **Table 4** offers a systematic map of the mitigation plans and policy tools that can be applied to each of the life cycle phases and addressed to the set environmental outcomes.

Table 4. Mitigation strategies across the NEV material supply chain.

Strategy Category	Key Measures	Targeted Life-Cycle Stage	Expected Environmental Benefits
Technological innovation	Low-impact mining, cleaner refining	Upstream	Reduced energy use and emissions
Material efficiency	Battery optimization, lightweighting	Manufacturing	Lower material demand
Circular economy	Recycling, second-life batteries	End-of-life	Resource conservation
Policy & regulation	EPR, environmental standards	System-wide	Impact internalization
Transparency & governance	Traceability, disclosure	Supply chain	Risk reduction, accountability

Ultimately, effective mitigation of environmental impacts from mining to mobility depends on integrating technological innovation, circular economy principles, and coherent policy frameworks. Isolated measures are unlikely to deliver substantial improvements unless they are embedded within a broader systems perspective. The following section builds on this discussion by identifying key research gaps and future directions that must be addressed to support informed decision-making and the continued evolution of sustainable NEV material systems.

6. Research Gaps and Future Directions

Even though the literature on the environmental implications of new energy vehicles is rapidly expanding, the material basis of electrified mobility is largely unknown. These loopholes are due to the constraints of available data and methodological difficulties in life-cycle analysis and uncertainties relating to technological and market change. These gaps need to be filled so as to create robust sustainability strategies and have intelligent policy and investment decisions based on holistic and trustworthy evidence. The section also presents the most significant gaps in research and future directions of the development of knowledge in en-

vironmental challenges in the NEV material supply chain^[11].

6.1. Data Limitations and Transparency in Material Supply Chains

The absence of quality and transparent, region-specific data, especially regarding the upstream supply chain stages, is one of the most adamant issues when evaluating the environmental effects of NEV materials. The mining and processing processes frequently take place in areas where the reporting of data is either scarce, inconsistent, or unavailable because of commercial confidentiality or insufficient regulatory conditions. Consequently, life-cycle assessments are often based on generalized or old data, which might not represent the current technologies or on-site conditions^[66].

Such data constraints are particularly acute for new materials and processes, and of by-product and co-produced materials, the environmental burdens of which are challenging to apportion. To improve data availability, not only must industry improve reporting and disclosure, but it is necessary to create standardized data collection procedures and collaborative platforms, which will foster information sharing among the stakeholders. The future studies must focus on combining the empirical and site-level data to minimize uncertainty and enhance the validity of the environmental

evaluation.

6.2. Methodological Challenges in Life-Cycle Assessment

Life-cycle assessment has been the most popular system to analyze the environmental performance of NEVs as well as their materials, but methodological inconsistencies still stand as an obstacle to comparability across studies^[67]. Variations in system boundaries, functional units, methods of allocation, and impact categories can result in divergence in conclusions about environmental benefits and trade-offs. Specifically, the management of battery life, recycling credits, and distribution of co-products creates great inconsistency in published outcomes. The other notable difficulty is that there is poor coverage of other types of environmental impact, other than greenhouse gas emissions. Although climate effects are comparatively well researched, other aspects of the same, like loss of biodiversity, land-use shift, and toxicity, are usually evaluated qualitatively, or they are not evaluated at all because of methodological limitations. The next stage in terms of future research is enhancing LCA methodologies in order to be able to more effectively estimate these impacts, such as by developing regionally differentiated characterization factors^[68,69].

Strategies of dynamic life-cycle assessment, which are sensitive to technological learning, transition of energy systems, and temporal variations of material flows, are also required. Existing condition-based tests can fail to capture long-term results of an environmental system that is changing very fast.

6.3. Integration of Social and Environmental Dimensions

The process of NEV materials is intimately connected with social and economic issues, such as the working conditions of the population, the health of the local population, and social consequences in influential areas of resource production. Nevertheless, the majority of the current research considers the environmental and the social dimensions as independent factors, which does not allow examining the trade-offs and synergies between sustainability objectives. The absence of comprehensive evaluation models impairs attempts to find materials or supply chain structures that

are environmentally desirable and socially troublesome, or the opposite. The future studies ought to attempt to fill this gap by combining environmental life-cycle assessment with social life-cycle assessment and other tools of socio-economic analysis. These combined approaches will help to create a more holistic view of sustainability issues and enhance more balanced decision-making. It is also an important research priority to develop indicators and datasets that would reflect on environmental as well as social performance^[70–73].

6.4. Uncertainty Associated with Emerging Technologies and Demand Pathways

The NEV's technology environment is changing at a high pace, giving a lot of unpredictability to the future of the material demand and the environment^[51]. New forms of electric battery, new motor designs, and new materials can change the material composition and intensity of use considerably, although their widespread use is questionable. Likewise, the avenues of future demand of NEVs will be influenced by various elements, such as policy encouragement, consumer attitude, and the trends of mobility at large. Scenario-based analysis is a helpful way of investigating this uncertainty, but the current scenarios usually pay attention to energy and emissions outcomes, and do not give a significant amount of information about the material supply chains. Future studies need to come up with combined scenarios that connect the adoption of vehicles, changes in technology, material requirements, and environmental consequences. These analyses could be used to determine the possible bottlenecks and guide the mitigation measures^[74].

6.5. Digitalization, Monitoring, and Decision Support Tools

The development of digital technologies provides new possibilities to enhance the evaluation and control of environmental effects involving NEV materials. Supply chains can become more transparent due to remote sensing, blockchain-based traceability systems, and artificial intelligence, and can be used to monitor environmental performance in real-time and act more responsively through a governance mechanism. Nevertheless, the use of such tools as they apply to critical materials is still in its infancy. Studies are required to assess

the use of digital solutions in monitoring the environment and in decision-making, and their scope and potential constraints. It involves knowing how digital tools can supplement the current regulatory systems and how the information provided by such systems can be incorporated into life-cycle assessment and in policy formulation^[12,67,75,76].

To conclude, there are still major gaps in research in data availability, methodological development, and comprehensive sustainability evaluation of NEV materials. There will be a need to fill these gaps by interdisciplinary cooperation, better control of data, and more progressive analytical approaches. Through continued research on these topics, future research in the future will be able to present stronger evidence on how to formulate environmentally responsible and socially equitable mobility transitions.

6.6. Toward a Standardized Framework for Comparing Battery Chemistries

To improve comparability across studies, future research should adopt a standardized framework for evaluating the environmental impacts of different battery chemistries and supply chain configurations. Such a framework should include several key elements. First, studies should apply consistent functional units, such as environmental impacts per kilowatt-hour of battery capacity or per vehicle-kilometer traveled. Second, harmonized system boundaries should cover the entire life cycle, including raw material extraction, refining, battery manufacturing, vehicle operation, and end-of-life management. Third, assessments should incorporate multiple environmental indicators, including greenhouse gas emissions, water consumption, land use, toxicity, and biodiversity impacts.

In addition, the framework should account for regional supply chain characteristics, such as electricity mix, mining technologies, and regulatory conditions, which significantly influence environmental outcomes. Finally, transparent assumptions regarding battery lifetime, recycling rates, and allocation methods for co-produced materials are necessary to ensure methodological consistency.

Implementing such a standardized evaluation framework would allow more reliable comparisons between battery technologies (e.g., Lithium Nickel Manganese Cobalt Oxide—NMC, Lithium Iron Phosphate—LFP, and emerging chemistries) and help policymakers and industry stakehold-

ers identify solutions that minimize environmental trade-offs across the entire NEV material supply chain.

7. Conclusion

New energy vehicles are being rapidly developed, which is one of the key pillars of the global strategies to decrease greenhouse gas emissions and become able to change the transportation sector. Although NEVs have obvious benefits regarding removing tailpipe gas emissions and enhancing the quality of urban air, this review shows that the environmental sustainability of electrified mobility cannot be fully perceived without a close consideration of the key materials on which it is based. The material life cycle of NEVs implies a set of intricate environmental problems that change the scope of impact up the supply chain and down the supply chains of the world, from mining and processing to manufacturing, use, and end-of-life management.

Through an integrated approach of mining to mobility, this article has condensed existing information on what kind of critical materials are employed in NEVs, their life-cycle routes, and the environmental concerns relating to each of the steps. Current analysis shows that energy usage, greenhouse gas, water, toxicity, land disturbance, and loss of biodiversity are disproportionately spread throughout the supply chain, with considerable negative effects occurring during the extraction of raw materials, processing, and battery manufacturing. These effects are extremely situational and are influenced by geological states and technological decisions, regional energy balances, and political organizations. Consequently, the environmental impact of NEVs differs significantly depending on the materials, technologies, and geographic regions. The review also highlights the need to cease climate-centered appraisals of the NEVs. Even though life-cycle greenhouse gas emissions represent an important measure, the other environmental dimensions, including water scarcity, ecosystem degradation, and the health hazards to human beings, can equally be important and, in certain situations, more locally relevant. The absence of consideration of these impacts may lead to problem shifting, i.e., advancements toward decarbonization may not adhere to alternative environmental and social goals. The life-cycle approach is also important in seeing the real sustainability benefits and preventing the unrecognized effects.

As explained in this article, mitigation measures are not the same solution to the environmental issues related to NEV materials. The opportunities are provided by technological innovation, such as cleaner mining and processing techniques, better battery designs, and material replacement to help lessen the environmental pressures. Recycling, reuse, and design to disassemble Circular economy solutions are essential to decouple NEV development and primary resource exploitation, though they require favorable infrastructure, market environment, and policies to be effective. Governance instruments, such as environmental policies, extended producer responsibility, and supply chain transparency programs, are vital in ensuring that technological and economic incentives are involved in attaining sustainability objectives.

Moving forward, the sustainability aspect of mobility will further develop with the ways in which societies may deal with the material basis of NEVs. There are still large research gaps in terms of data availability, methods of life-cycle assessment, and the incorporation of environmental and social aspects. To fill these gaps, interdisciplinary cooperation will be necessary, enhanced transparency in global supply chains, and the creation of dynamic and progressive analytical tools in accordance with the changing technologies and demand trends. These findings highlight that decarbonization strategies must be evaluated within a broader environmental context. Policies and technologies that reduce carbon emissions should also be assessed for their implications for water resources, ecosystem integrity, and local environmental quality to avoid shifting environmental burdens across impact categories or geographic regions.

To sum up, new energy vehicles would make significant contributions to climate mitigation, but their long-term environmental impact depends on the responsible handling of important materials in their life cycle. To guarantee that the transition to electrified mobility rather than fossil-based mobility will result in the true sustainability of the environment, a concerted effort will be required on all levels of research, industry, and policy. The stakeholders can contribute by identifying and managing the environmental concerns related to mining and mobility to ensure that the development of the NEV systems is no longer low-carbon, but also resource-efficient, environmentally friendly, and consistent with other sustainability goals.

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The author declares no conflict of interest.

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