

Toward a Sustainable Future of Electric Vehicles: Environmental Challenges, Battery Recycling, and Policy Recommendations

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Abstract. While electric vehicles (EVs) offer environmental advantages by eliminating tailpipe emissions, their lifecycle presents significant sustainability concerns. The mining of key battery materials such as lithium, cobalt, and nickel often leads to environmental degradation and human rights violations, particularly in under-regulated regions. Moreover, the global recycling rate of retired EV batteries remains alarmingly low. This paper investigates the environmental implications of EV battery production and disposal and proposes policy interventions, including enhanced recycling mandates, producer responsibility schemes, and stricter mining standards. It also advocates for material recovery targets and the use of IoT-based tracking to ensure responsible battery lifecycle management. These integrated strategies are essential to support the sustainable growth of the EV industry while mitigating environmental and social impacts.

Keywords: Electric vehicles; Environmental impact; Recycling policy; Battery lifecycle.

1. Introduction

1.1 Background

In the 21st century, the global push for Electric vehicles (EVs) to combat the greenhouse gas effect and reduce dependence on fossil fuels has enormously impacted people's daily lives. The greenhouse gas effect refers to the warming of Earth's atmosphere resulting from the accumulation of various greenhouse gases that trap infrared radiation reemitted from the Earth. Transportation is one of the major sources of greenhouse gas emissions globally, accounting for nearly 15%. Government and industries around the world have started to collaborate and promote EVs to completely replace Internal combustion engine vehicles (ICEVs) [1]. For instance, in China, the government subsidizes consumers up to RMB 20,000 (USD2780) for trading ICEVs for EVs. The transition from ICEVs to EVs is a critical step for reaching a more sustainable future [2]. In particular, electric vehicles could reduce greenhouse gas emissions, improve air quality, and decrease reliance on non-renewable fossil fuels.

However, while electric vehicles offer several benefits compared to ICEVs, they also raise concerns regarding the environmental consequences of battery manufacture and disposal. The extraction of raw minerals such as cobalt, natural graphite, lithium, manganese, and nickel often leads to soil erosion and groundwater contamination, especially in countries where regulations are poorly enforced [3]. Simultaneously, when batteries could not provide enough driving distance and energy storage capacity, these batteries present a serious issue to the environment. In less economically developed countries, there might be issues with recycling electric vehicles' batteries. For instance, if batteries are not recycled, valuable resources and minerals might be wasted, increasing the demand for mining, which further degrades the environment and forms a vicious cycle. Finally, the improper disposal of batteries could also have a devastating consequence for the environment, such as the release of toxic substances.

While EVs could be a promising solution compared to ICEVs to reduce greenhouse gas emissions and slow down global warming, their batteries still require the extraction of rare minerals and cause intense damage to the environment. These issues raise a critical question related to the overall sustainability of EVs, particularly in the production of EV batteries, which are not managed carefully and have a negative influence on humans and nature.

1.2 Vehicle Emissions and Contribution

Fig. 1 illustrates the distribution of CO₂ emissions produced by different kinds of transportation in 2023. The graph clearly shows that 75.2% of the emissions caused by transportation all come from road transportation. Road transportation, including trucks, buses, motorcycles, and cars, emits the most CO₂ compared to other transportation modes like rail and aviation.

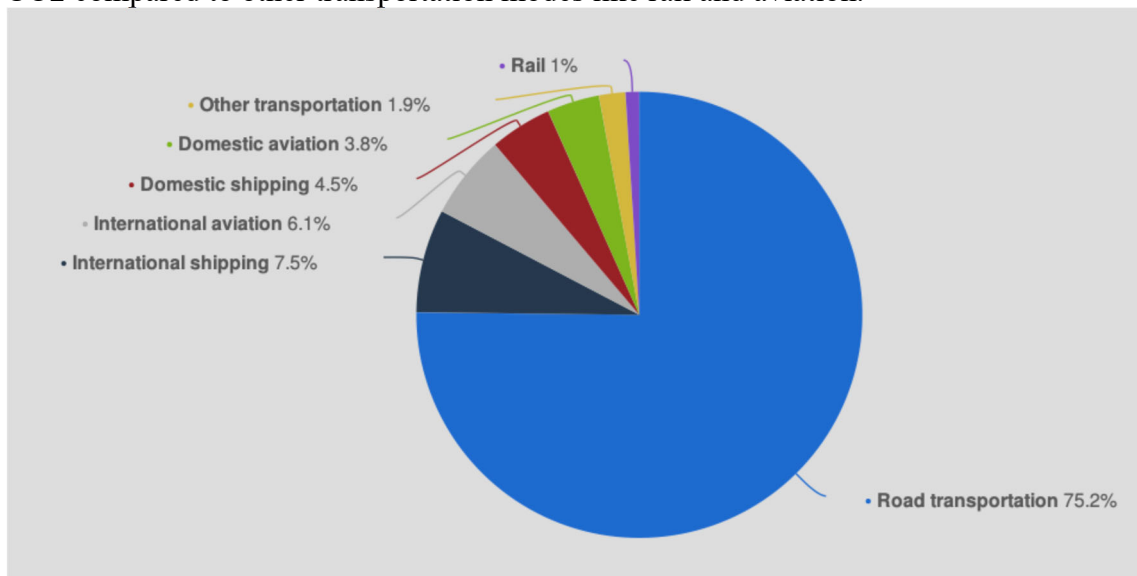


Fig. 1 Distribution of carbon dioxide emissions produced by the transportation sector in 2023

The graph clearly illustrates how much damage automobiles have caused and the urgent need to transition from ICEVs to EVs [4]. Reducing emissions could also help car owners save money on gasoline. Furthermore, reducing emissions also requires a lot of technological innovation and infrastructure development for EVs to benefit.

There are several environmental impacts caused by EV production, such as battery waste, a high carbon footprint, and low recycling waste. The extraction of minerals like Lithium requires a lot of water, particularly in Brine deposits. For example, extracting one ton of lithium would require around 500,000 liters of water [5].

2. New Energy Vehicles

2.1 Basic Operation of Electric Vehicles

There are many types of new energy vehicles, including all-electric vehicles, plug-in hybrid vehicles, and hybrid electric vehicles. Fig. 2 shows several components of EVs. Electric vehicles function by using a battery that stores electrical energy for use. A battery pack is made out of numerous cells grouped into modules. The power is transformed from a direct current (DC) battery to alternating current (AC) for the electric motor. The AC is when the alternator converts the alternating currents into direct current using a regulator or rectifier, and the DC refers to the type of electrical current that powers different components of the car. The accelerator pedal sends a signal to the controller, which allows the car to receive instant torque and speed by adjusting the frequency of the AC power from the inverter to the motor. Then the motor connects to the wheel and powers the electricity to turn the wheels. When the brakes are stepped, the motor stores the energy and power and transfers it back to the battery [6].

The key components of an electric vehicle are the electric motor, inverter, battery, battery charger, controller, charging cable, and others. The electric motor is where all of the electrical energy is converted into mechanical energy. The inverter is where all the DC electricity is transformed into AC electricity. A battery's main purpose is to store all of the electrical energy and provide power to all devices. The battery charger is to restore all of the electrical charge of a battery and allow it to be used again [7]. The controller is responsible for managing different vehicle systems, ensuring that all

of the components are working together and efficiently. Charging cables have the purpose of transferring the electrical power from a power source to different devices and enabling them to recharge their batteries.

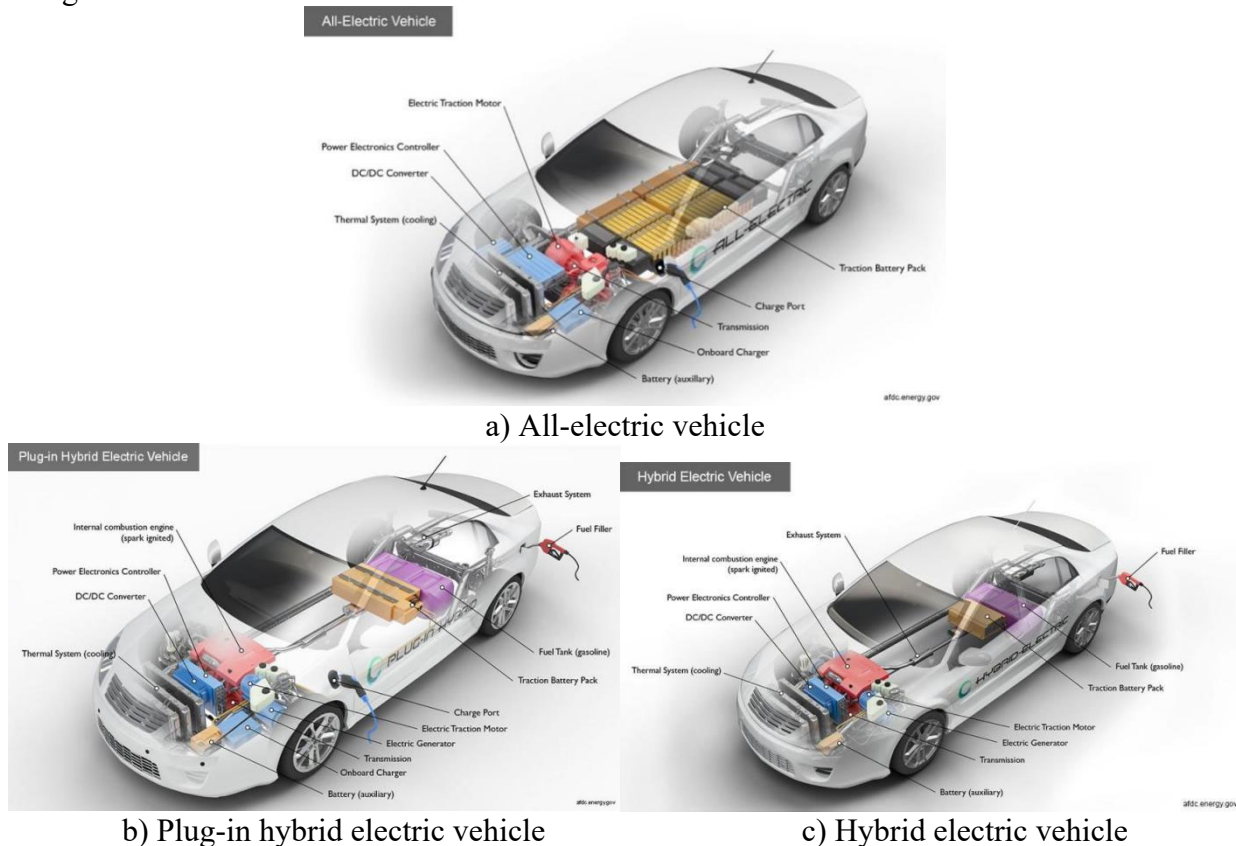


Fig. 2 Key components of different vehicles

A plug-in hybrid electric vehicle has many similar components compared to electric vehicles. For instance, the electric motor, battery pack, power electronics, charging port, and regenerative braking system all could be similar in both of these types of cars. However, the difference is that plug-in hybrid vehicles usually have both a fuel filler and a charge port, as well as an internal combustion engine and exhaust system. Additionally, plug-in hybrid EVs are more complicated than full EVs [8]. A plug-in hybrid is a car that has both an electric motor and a gasoline engine. Where drivers charge the car by plugging it in, and drive for a short distance, only using the electric motor. When the battery runs out of electricity, the gasoline turns on and powers the car like other regular gasoline cars.

The main difference between PHEV and hybrid cars is that PHEV can be charged by plugging into an external power source and can drive longer compared to a regular hybrid. A regular hybrid cannot be plugged in and relies mostly on a gasoline engine, with only a short amount of electricity. Additionally, regular hybrids are usually way cheaper compared to PHEVs. PHEVs are expensive because they have larger battery packs, more powerful electric motors, and more complex powertrains.

2.2 Statistics on Electric Vehicle Usage

Fig. 3 shows a gradual increase from 2013 to 2023, where electric vehicles raised production from 0.2 million to 13.8 million. It is observed that from 2020 to 2021, there was a significant increase in the production of EVs. There are several reasons why the EVs sold annually tripled compared to the previous year in 2021. The main causes are government policies, consumer demand growth, and recovery from the COVID-19 disruption to the economy. In 2021, after the COVID-19 pandemic, many governments stood out and offered financial incentives for many industries to produce EVs [5]. Furthermore, governments have promoted car buyers to purchase EVs instead of ICEs. Additionally, a lot of people have started to be aware of climate change and air pollution, causing the demand for cleaner transportation.

The second reason might also be that electricity could be more affordable than gasoline, offered at a lower cost per kWh, with longer driving distances, and faster charging times, all of which have led to the increase of EVs. Finally, after COVID-19, the overall economy has grown back, and the demand for transportation has increased as well. From 2020 onwards, there has been explosive growth and diversification for EVs. There are now more low-cost options, luxury EVs, and even trucks. Many countries have started to invest money in their local production of EVs. To conclude, from 2020 onwards, the production and sale of EVs have increased significantly due to government incentives and public demand for cleaner and cheaper automobiles.

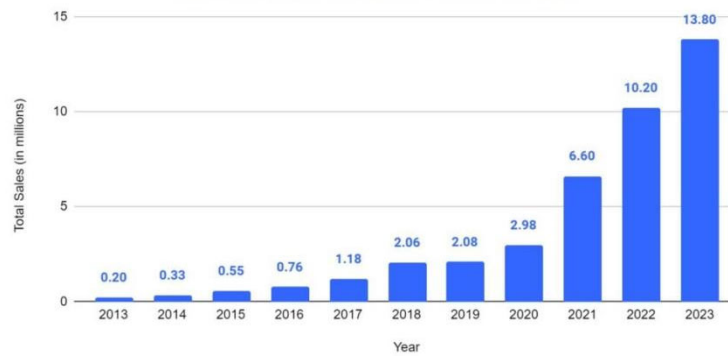


Fig. 3 Number of electric cars sold annually

2.3 Impact of NEVs on CO₂ Emissions

Automobiles have always contributed a lot to CO₂ emissions. The average vehicle emits about 400 grams of CO₂ per mile, which is about 4.5 metric tons of CO₂ per year. In addition to CO₂, cars also emit methane, nitrous oxide, and hydrofluorocarbons from leaking air conditioners that could all be harmful to human health. Compared to gasoline cars, EVs generally emit a smaller amount of GHGs due to air conditioner and HFC leakage. EVs have a battery instead of a gasoline tank, so the electric motor does not produce any tailpipe emissions. However, the production of batteries, such as those used in power plants, might generate massive emissions. The production of EV batteries could range from 2400 kg to 16000 kg. For instance, the Tesla Model 3 has around 80 kWh of lithium-ion battery. CO₂ emissions for the production of this battery would range from 2400 kg to 16,000 kg per battery [8]. The emissions from the production of different EVs' batteries would also impact the environment in other ways, such as disposal issues, leakage of acid, etc. On the other hand, petrol cars have emitted a huge amount of CO₂ compared to EVs, making EVs a solution to slow down global warming. Diesel and gasoline engine cars have emitted around 9-12.5 % of the world's total CO₂ emissions into the atmosphere [9].

The carbon footprint of EVs' production is way higher than that of traditional ICEVs due to their battery manufacture. However, the EVs have a way lower carbon footprint compared to ICEVs over their lifespan due to the elimination of tailpipe emissions and the reliance on electricity, specifically when the electricity is generated from renewable resources [10]. Nevertheless, there are still several factors to consider when estimating the carbon footprint of EV battery production, such as production location, lithium-ion batteries, and manufacturing process. As shown in Fig. 4, hybrid vehicles have an estimated carbon footprint of 6.5, and gasoline vehicles have an estimated carbon footprint of 5.6, which is the lowest.

Vehicle Type	Estimated lifecycle emissions (tonnes CO2e)	Proportion of emissions in production	Estimated emissions in production (tonnes CO2e)
Standard Gasoline Vehicle	24	23%	5.6
Hybrid Vehicle	21	31%	6.5
Battery Electric Vehicle	19	46%	8.8

Based upon a 2015 vehicle in use for 150k KM using 10% ethanol blend and 500g/KWH grid electricity

Fig. 4 Estimated carbon footprint of vehicles

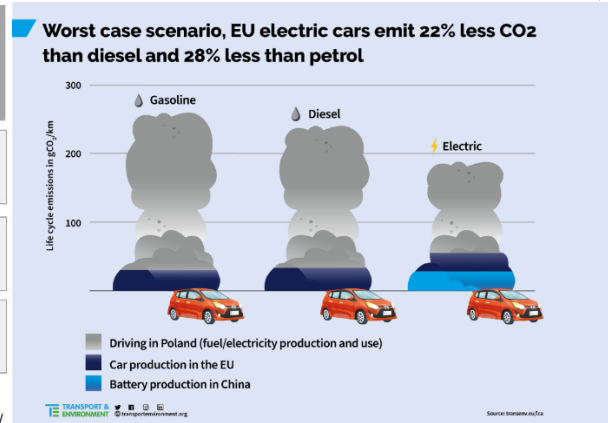


Fig. 5 Vehicle whole life carbon emissions

As shown in Fig. 5, EVs' production of batteries emits a lot of CO₂; however, they still have an overall lower CO₂ emission compared to diesel and gasoline cars over the life span of the vehicles. The average carbon footprint of ICEVs is around 250 g/km, while that of electric cars is only about 180 g/km.

Although EVs do not produce any tailpipe emissions, in the production of EVs, lithium-ion batteries require an intense amount of energy and release greenhouse gases like CO₂ and methane. In addition, the extraction of these raw materials also requires a lot of energy and can lead to environmental issues such as habitat loss, soil erosion, and water contamination. Finally, the manufacturing process of EVs, including the production of battery packs and other parts, also contributes to greenhouse gas emissions. However, compared to internal combustion vehicles, EVs produce less greenhouse gas emissions. ICEVs' manufacturing emissions release more greenhouse gas, compared to EVs, because ICEVs don't require large batteries. However, producing the engine and transmission for the ICEVs still requires more emissions compared to EVs [11].

3. Electric Vehicle Battery

3.1 How Batteries Work

EV batteries drive the motor, and the motor powers the wheels to work. EVs contain a large battery pack that sends power to the onboard electric motor. Then the motor drives the vehicle's wheels to move on the road. Additionally, there is another battery pack on the car that could function as special features like AC or heating. Each EV battery functions similarly to a phone's battery, containing both a cathode (positive) and an anode (negative) that form a lithium-ion battery [12]. In the middle, the electrolyte allows movement of ions between the electrodes when connected to an electric circuit, and the electrons would transfer from the anode to the cathode through the external circuit. As shown in Fig. 6, the anode and cathode are on both sides and in the middle, containing the separator that helps prevent short circuits by preventing direct contact between the Anode and Cathode.

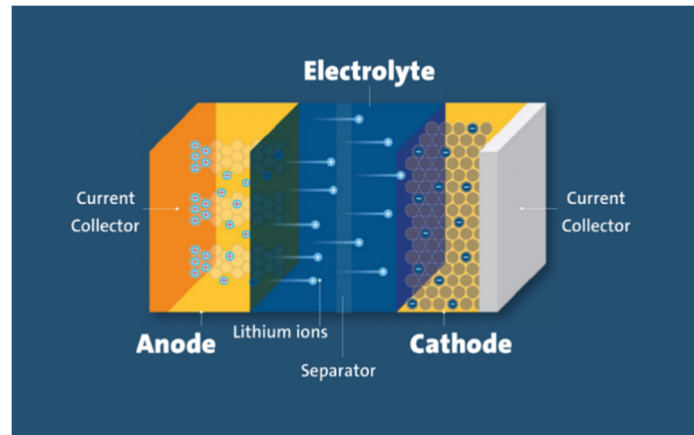


Fig. 6 Lithium-ion batteries

3.2 Battery Manufacturing and Environmental Impact

77% of the world's production of EV batteries comes from China. Other countries, such as the United States, India, and Europe, are working to increase their production of batteries. Nevertheless, China still holds the world's largest supply of raw materials for producing batteries.

The manufacture of EV batteries begins with preparing all of the raw materials needed. The raw materials come from mining in different places, especially in Congo, which accounts for approximately 68 per cent of the world's cobalt. Raw materials are like lithium, nickel, cobalt, and graphite, and they get refined and packed together to be put inside the anode. Then the anode contains graphite on copper foil and the cathode has the lithium-metal oxides on Aluminium film. They are separated by a separator, filled with electrolyte. Then sealed into battery cells to test whether there are any leaks or moisture that could cause fire. Then, cells are grouped into modules using ultrasonic welding for electrical connection and sheathed into a protective container. Then the modules are combined and assembled into the battery pack, with different connecting machines and a cooling system to prevent fire [11]. Then the battery is tested for control of voltage, capacity, and power output to maintain the battery. Finally, the fully tested battery pack is shipped to the EV assembly line, where it will be installed into the car's chassis.

However, there are some environmental consequences that might be caused by the production of batteries, such as water pollution, air pollution, resource depletion, and disposal challenges. Resource depletion and habitat destruction may result from the mining of lithium, cobalt, and other battery minerals, potentially leading to habitat destruction and the displacement of animals during the mining process. Water pollution is another consequence of battery production, as the mining of substances can lead to improper disposal and pollute water sources with toxic substances. Additionally, battery production generates organic waste, including nitrate and phosphate. Production of batteries can also indirectly lead to air pollution through energy consumption, as factories emit large amounts of CO₂ and sulfur emissions from the use of coal power. The result is that CO₂ would contribute to climate change, SO₂ would cause acid rain and respiratory issues, and Nitrogen oxides (NO_x) would lead to smog and lung diseases. Resource depletion is caused by the extraction of materials like lithium, cobalt, and nickel for batteries [13]. When resources are not recycled properly, they are thrown away, leading to disposal challenges.

3.3 Mining for battery materials

EV batteries are mostly extracted in Australia, Chile, Argentina, and the Congo. They play a crucial role in the global supply of minerals and raw materials used in different technologies such as EVs, electronics, and jewelry. Half of the world's cobalt comes from the Democratic Republic of Congo (DRC) and is supplied to the world's biggest automotive industry, such as China. The world's most in-demand minerals, including Lithium, Cobalt, Nickel, and others, are used to produce EV batteries and other technologies. However, the limitations are that there are numerous environmental

and social consequences caused by mining, such as deforestation, habitat loss, soil erosion, water and air pollution, child labor, climate change, health hazards, and impact on local communities.

3.3.1 Human rights issues

Child labor and forced labor are very common in countries like the DRC, where children are forced to work in hazardous environments to mine different minerals. Over one million children are engaged in the mining of minerals in Africa, posing a threat to children's safety and health. Additionally, it was very often that some teenagers worked around 24 hours in the mines and earned little income for their house and food. In the mines, the temperature could be as low as $-50\text{ }^{\circ}\text{C}$ or as high as $60\text{ }^{\circ}\text{C}$. Lastly, the health consequences of mining on the children are devastating, even causing lung cancer that could lead to death.

The expert has stated that the working conditions in the mines in Congo are fatal. Some mines could even cause explosions and release gases, exposing people to dangerous chemicals such as silica dust, asbestos, radon, carbon monoxide, hydrogen sulfide, methane, and carbon dioxide. On top of that, the teenagers working in mines in Congo do not even have any professional equipment like helmets, safety glasses, ear protection, masks, gloves, etc., to prevent them from inhaling different fatal chemicals [14].

Nevertheless, the production of EVs still has the most impact on the locals living near the mines, leading to economic growth in local communities and decreasing the unemployment rate in the country. However, the negative consequences are that locals are being exposed to various chemicals through drinking water near the mines and inhaling air contaminated with these chemicals. Additionally, mining activities could destroy local habitats, leading to a decline in biodiversity and impacting the traditional food source for locals.

3.3.2 Natural impacts

The environmental degradation of the manufacture of EVs are ecosystem destruction, resource depletion, pollution, climate change, and resource depletion. The production of EVs has produced over 46% of CO₂ emissions compared to 26% of ICEVs. Additionally, the transportation of batteries to China leads to bigger CO₂ emissions and an increased carbon footprint. Overall, this leads to more people being exposed to Carbon Dioxide and leads to global warming, which has devastating consequences for both humans and nature.

Firstly, deforestation is caused by mining when mining operation clears out a lot of trees, which would decrease the amount of CO₂ absorbed by the trees and cause there to be fewer trees that would release oxygen for humans to breathe in. This process has a significant impact on the environment, causing there to be water pollution, habitat loss, climate change, and soil erosion. Deforestation causes habitat loss because when a forest is cleared, the animals lose their shelter, which disrupts the ecosystem and potentially drives some species to extinction. For instance, the Democratic Republic of Congo (DRC), which supplies the world's 60% of cobalt for the cathode in EVs' lithium-ion batteries, has destroyed over 10,000 hectares of rainforest, resulting in habitat loss and also causing animals to lose their shelter. For instance, the Grauer's Gorilla was critically endangered in 2021 [15]. Grauer's Gorillas are endemic to the DRC and play an important role in seed dispersal and maintaining rainforest diversity. However, the population dropped from 17000 in 1995 to less than 6500. To conclude, forest plays a crucial role in the ecosystem in regulating climate, the water cycle, and soil stability. However, deforestation would disrupt these natural processes, leading to different issues.

Second, water pollution from mining is caused by heavy metal contamination. When metals such as cobalt, arsenic, copper, zinc, lead, cadmium, and silver—found in underground mines or excavated rock—are exposed to water, the water will be contaminated. Additionally, non-essential heavy metals like gold and mercury, while having no biological role, are highly toxic when ingested. This can lead to species extinction and also cause health problems for people who consume contaminated animals. For example, the Lithium Mining in Chile's Atacama Desert released over 500,000 gallons of contaminated wastewater into the San Pedro River and the Salar de Atacama's groundwater. In

addition, fish populations have declined because toxic metals directly kill the fish by damaging their gills and organs. Furthermore, metals like arsenic and mercury bioaccumulate in fish tissues, disrupting their body systems and damaging processes such as reproduction, embryonic development, and immune function. For example, mercury can cause neurological damage, impaired growth, and reproductive tissues. Humans could also be affected by mercury exposure through consuming contaminated fish. Lastly, habitat destruction caused by the mine spill has numerous impacts, including increased acidity and heavy metal contamination, which make the river less suitable for many aquatic species, reduce biodiversity in the ecosystem, and impact the overall health of the ecosystem, potentially leading to ecosystem disruption.

Third, Global warming is caused by mining because the equipment used in mines releases greenhouse gas emissions, particularly from the extraction of different minerals and metals, the process of fossil fuels, and the energy-intensive nature of mining operations. While mining represents a small fraction (4-7%) of released greenhouse gas emissions, the impact is still significant compared to fossil fuel combustion. These emissions trap heat in the atmosphere, directly leading to increased global temperatures. Besides, the energy demands of mining often rely on a fossil fuel-based power plant, further increasing the CO₂ emissions. For instance, during coal mining, methane trapped under coal seams is released during extraction, leading to methane emissions. Lastly, when coal is exposed to air, it releases CO₂ and sometimes even CO, contributing to greenhouse gas emissions. To sum up, the loading of large diesel trucks responsible for transporting various minerals and materials from mining sites to factories releases a significant amount of carbon dioxide into the atmosphere, contributing to global warming. For example, in Australia, the cobalt mines cause more global heating than all of Australia's car emissions. In 2019, coal companies leaked over 898,000 tons of Methane into the atmosphere, representing 5% of Australia's total GHG emissions.

Finally, air pollution from mining has numerous consequences, including respiratory illnesses, cardiovascular problems, environmental degradation, and habitat destruction. For instance, in mining, miners would blast large quantities of minerals and metals to find cobalt and other minerals. However, during blasting, fine particles are released into the air, and they contain heavy metals and other pollutants that could affect the air quality and also impact the locals living near the mining sites. For instance, in regions like Lubumbashi and Kolwezi, mining operations involve blasting and drilling that would release dust and fine particle matter that contain toxic metals like cobalt, lead, and uranium. Additionally, smelting of copper-cobalt ores like chalcopyrite would release Sulfur Dioxide and cause acid rain that could damage crops and acidify rivers and lakes such as the Lualaba River.

4. Battery Recycling

4.1 Recycling Process

The recycling process of EVs is sophisticated, comprising numerous processes that play a crucial role in the sustainable management of various minerals and resources. As the demand for EVs rises globally, the proper management of waste is becoming more important to sustain the world's resources, reduce reliance on mining, and prevent hazardous chemicals from going into landfills. The recycling process starts with a safe cleaning and transportation of extra resources and batteries, which require professional skills to handle their potential fire risk from broken circuits.

First, the unused materials are transported in UN-certified containers to prevent fires in recycling facilities. Once at the facilities, the batteries undergo a discharging time that could eliminate all of the remaining voltage and electricity. Then they are disassembled both automatically and manually to separate materials that can be reused from those that need to be torn apart. Furthermore, at big EV manufacturing companies like Tesla or Volkswagen, they employ robotic arms and machines to efficiently break down battery packs into individual cells. These cells are then crushed and shredded in a nitrogen container to prevent the combustion of reactive materials. Then the shredded materials are processed to isolate "black mass", a fine powder containing valuable metals like lithium, nickel, manganese, and graphite.

Second, the process involves metal extraction, which can be achieved through different methods. Pyrometallurgy, used in companies like Umicore, involves refining the black mass at high temperatures around 1400-2000 °C to recover cobalt, nickel, and copper through lithium. The high-temperature approach produces a molten alloy rich in cobalt, copper, nickel, and lithium. While Pyrometallurgy requires a lot of energy, it offers a high capacity and excellent recovery rates for base metals of about 95%, making it suitable for large-scale metal production. On the other hand, hydrometallurgy, used by companies like Li-cycle and Redwood Materials, is efficient for extracting metal by using a solution to recover metals from ores, concentrates, and recycled materials. In more specific terms, the extraction and recovery of unused materials from the ores through leaching the black mass with aqueous solution, such as acids or bases, to dissolve valuable metals such as lithium, cobalt, nickel, and copper. Then the process is followed with precipitation, solvent extraction, or ion exchange to recover these metals in high purity for reuse in battery production or other actions [11].

After extraction, the recovered metals undergo purification to meet the standards before being sold back to manufacturers or people who sell used batteries and EVs. For instance, recycled lithium-ion can be used again in new battery production, while recovered nickel and cobalt are refined into special chemicals that could serve as the fundamental building blocks for manufacturing new battery cathodes. Lastly, other components like plastics, electrolytes, and graphite are processed to create valuable secondary materials that could be reused in battery production and other processes.

4.2 Environmental and Economic Benefits

Recycling EVs has numerous environmental benefits, primarily by reducing the amount of CO₂ emitted into the atmosphere and reducing the need to extract new raw materials. It also helps with reducing landfill waste, saving energy, slowing down climate change, reducing pollution, etc.

First, the recycled EV parts could reduce the amount of CO₂ emitted into the atmosphere by decreasing the need for new raw materials, because when raw materials are mined, the mining technologies require a lot of energy that comes from burning fossil fuels that emit CO₂ into the atmosphere. However, if EVs' parts are recycled, then it would promote a circular economy by allowing the reuse of valuable resources and minerals in the new battery production. Recycling EV components could also prevent landfill waste because when materials are recovered, they wouldn't be buried and leach out harmful substances that might negatively impact humans and nature. Additionally, it could save up energy used by mining technologies when reducing the amount of minerals mined. Finally, it could also reduce pollution by reducing air pollution caused by the mining of minerals and water pollution caused by the leaching of dangerous chemicals from landfill waste.

The economic benefits of recycling EVs are creating new jobs, lowering the cost of EVs, lowering mineral costs, local economic development, and expansion of new markets. First, recycling EV components could create jobs for people who could handle the technologies for mining and cleaning up batteries, and extracting the materials that could still be reused inside the batteries. Second, when minerals and materials are reused, it could reduce the cost of EVs, providing more people with the opportunity to purchase EVs. Therefore, it could decrease unemployment rates and trigger the economy to grow. As RMI studies suggest, recycling could add \$11B to \$40B to the global economy [4]. Third, mineral costs would decrease, allowing more people to purchase minerals and produce various technologies. Furthermore, recycling EVs could help encourage innovation and green industries to continue developing because recycling EVs would require a lot of new technologies to recycle different components of EVs. Lastly, it could support the government by generating additional tax revenue, which the government could then invest in more companies that recycle not only EVs. To conclude, recycling EVs has numerous benefits to the environment and economy.

5. Conclusion and Suggestions

The accelerating adoption of electric vehicles (EVs) benefits the environment by eliminating tailpipe emissions, yet important limitations remain. EV production still depends on fossil energy,

and the disposal of end-of-life lithium-ion batteries poses nontrivial risks. As this study shows, battery manufacturing—driven by intensive mining of lithium, nickel, and cobalt—can exacerbate flooding, deforestation, habitat loss, air pollution, resource depletion, human-rights abuses, and landfill waste. Meanwhile, only about 1.7% of retired EV batteries are recycled globally, amplifying both pollution and material loss. These challenges call for an integrated policy and technology response.

Governments should tighten regulation of mining and battery recycling while deploying incentives that shift industry behavior. Producer responsibility (EPR) schemes should make manufacturers accountable for collection and recycling, with tax relief for compliance and penalties for non-compliance. Environmental and labor standards—particularly in high-risk regions such as the DRC—must ban child labor, cap effluents, and require water-recycling systems in lithium extraction to cut freshwater use by at least 50%. Alignment with the EU’s Battery Regulation and the Critical Raw Materials Act can provide clear targets and market signals (by 2030: 10% extracted, 40% processed, and 25% recycled within the EU), accelerating a circular, lower-impact supply chain.

To curb primary mining and stabilize costs, mandatory recovery targets are warranted: $\geq 95\%$ for cobalt and nickel and $\geq 80\%$ for lithium, reflecting both environmental gains and current technical feasibility. Continued R&D is needed to raise lithium recovery and improve process efficiency. In parallel, lifecycle governance should be strengthened with IoT-based traceability to monitor battery health and location from collection through processing, ensuring proper handling and preventing illegal disposal. Taken together, rapid EV deployment coupled with robust governance, ambitious recovery thresholds, and data-driven oversight can materially reduce emissions and waste, conserve critical minerals, and improve environmental and social outcomes.

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