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Article

Exploring the link between energy resources and global biodiversity

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Abstract: The availability of energy resources and their relationship with global biodiversity are critical concerns that demand urgent attention, especially given the world's rising energy demands. This review paper examines the impacts of both renewable and non-renewable energy sources on biodiversity across different ecosystems. The extraction and use of fossil fuels—coal, oil, and natural gas—have led to severe pollution, habitat destruction, and climate change, threatening countless species and ecosystems. The processing and consumption of these non-renewable resources continue to accelerate biodiversity loss. While renewable energy sources—such as solar, wind, bioenergy, and hydropower—offer a pathway to reducing greenhouse gas emissions, they also pose biodiversity challenges. Large-scale solar farms alter land use, causing habitat fragmentation. Wind farms, while crucial for clean energy, threaten bird and bat populations. Hydropower projects disrupt river ecosystems, affecting aquatic species' migration patterns. Similarly, bioenergy production often relies on extensive monoculture farming, leading to deforestation, agrobiodiversity loss, and competition with food crops. This paper explores mitigation strategies, emphasizing ecological offsets and habitat restoration as key conservation tools. These approaches align with global frameworks such as the United Nations Sustainable Development Goals (SDGs), ensuring that energy policies integrate biodiversity protection. The review highlights the importance of balancing energy expansion with environmental sustainability through strategic policymaking. A region-specific approach is essential, given the varying energy needs and ecological sensitivities across countries. Overreliance on energy-intensive technologies in some regions exacerbates environmental degradation, necessitating countermeasures to prevent resource overexploitation. By incorporating biodiversity-conscious energy strategies into decision-making, it is possible to achieve a sustainable balance between energy production and conservation. This analysis underscores the need for globally coordinated yet locally adaptive policies to ensure that the transition to renewable energy does not come at the expense of biodiversity.

Keywords: energy resources; global biodiversity; renewable energy; environmental impact; biodiversity conservation

1. Introduction

Understanding the interaction between energy resources and biodiversity is crucial for promoting sustainable development globally. Both renewable (non-conventional) and non-renewable (conventional) energy sources play a significant role in shaping global development, species distribution, and ecosystems [1,2]. Non-renewable energy resources (e.g., fossil fuels and nuclear energy) are defined as energy sources with limited availability that cannot be replenished within a human timespan. These resources are typically derived from the remains of ancient plants and animals

that have undergone extreme heat and pressure over millions of years. Due to the extensive time required for their formation and their finite supply, non-renewable resources are not classified as renewable energy [3–5]. Non-renewable energy resources share several key characteristics. Firstly, they have limited availability; once extracted and used, these resources cannot be replenished quickly enough to meet ongoing demand. Secondly, non-renewable resources require millions of years to form [4,6]. For example, fossil fuels are created from the remains of extinct plants and animals that undergo geological processes such as condensation and combustion over long periods. Additionally, fossil fuels have a high energy density, making them highly efficient for energy generation [7]. This energy efficiency, coupled with their role as primary drivers of industrial growth and electricity production, is why fossil fuels continue to be widely sought after despite their limited supply [8–11].

Renewable energy refers to energy derived from natural sources that are replenished constantly and can be sustainably used without depleting the resources [3]. These sources include solar, wind, hydropower, geothermal, and biomass. Renewable energy is sustainable, as these resources are naturally replenished, ensuring their availability over the long term. It typically has a lower environmental impact compared to non-renewable energy sources [4,5]. For example, solar and wind energy produce little to no greenhouse gas emissions, helping mitigate climate change. Renewable energy systems often rely on decentralized production, where energy is generated at or near the point of use, reducing energy transmission losses and improving energy security [5]. Renewable energy sources, especially solar and wind, are abundant and widely distributed, making them accessible across most regions. They provide a cleaner and more sustainable alternative to fossil fuels, reducing environmental impact and promoting long-term energy security [3].

However, both renewable and non-renewable energy resources have a significant impact on the distribution of species and ecosystems globally. Their extraction, production, and use of these resources contribute to environmental challenges, including pollution, habitat loss, and climate change, making them key drivers of ecological transformation [1,2,4]. While fossil fuels—coal, oil, and natural gas—have been fundamental to human civilization's progress, their continued reliance has devastating effects on the atmosphere. Excessive greenhouse gas emissions from their extraction and use drive climate change, leading to severe environmental degradation and threatening ecosystems worldwide [2,3]. Moreover, drilling and mining activities cause significant habitat loss and degradation, accelerating the decline of vulnerable species and intensifying the biodiversity crisis [4,6]. In contrast, solar, wind, hydro, and bioenergy are considered more sustainable alternatives as renewable energy sources. While they have a significantly lower environmental impact than fossil fuels, they are not entirely free from ecological concerns. Large-scale wind and solar farms can disrupt ecosystems, leading to habitat fragmentation and wildlife displacement, while bioenergy production may still contribute to greenhouse gas emissions [5]. Clean energy projects like hydropower come with certain downsides, such as disrupting ecosystems and aquatic species' migratory patterns [4,6]. The application of bioenergy, which relies on cultivable lands, brings worries pertaining to deforestation and food competition [6].

A well-designed energy policy that prioritizes sustainable practices among energy producers provides a balanced approach while promoting afforestation. Mitigating the negative impacts of energy production on biodiversity requires the implementation of strategies such as ecological offsets, habitat restoration, and the integration of biodiversity-friendly technologies [7]. Hydropower projects that reduce the size of lakes, along with survival kits for internally displaced people and other resources aimed at achieving sustainable development goals, cannot be effectively supported without international aid and comprehensive research [8]. In general, the relationship between energy resources and biodiversity is deeply influenced by sociological factors, including governance, cultural values, and economic systems. Governance structures play a crucial role in shaping energy policies and environmental protections [9]. Countries with strong regulatory frameworks can implement sustainable energy practices that minimize biodiversity loss, whereas weak governance may lead to unchecked exploitation of resources, worsening environmental degradation. Cultural factors also shape energy use and conservation efforts. Indigenous communities, for instance, often have traditional ecological knowledge that promotes sustainable resource management [10]. However, large-scale energy projects frequently marginalize these communities, leading to conflicts over land and resource rights. Similarly, consumer behaviors and societal attitudes toward energy efficiency influence demand, affecting the scale of energy production and its ecological consequences. Economic systems further impact biodiversity through energy investments and subsidies. Fossil fuel-dependent economies may resist transitions to renewables, prioritizing short-term economic gains over long-term sustainability [10]. Meanwhile, global energy markets drive land-use changes, sometimes exacerbating deforestation and habitat loss for bioenergy or hydropower projects. This review explores recent research on the relationship between energy and biodiversity, providing essential context while highlighting key findings and identifying gaps in current knowledge.

2. Literature review methods

The published, peer-reviewed articles on renewable and non-renewable energy were retrieved from international scientific databases and publishers. These included but are not limited to Springer (https://www.springer.com/gp), Taylor & Francis (https://www.tandfonline.com/), Scopus (https://www.scopus.com/home.uri), PubMed (https://pubmed.ncbi.nlm.nih.gov/), Elsevier (https://www.elsevier.com/), Wiley-Blackwell (https://www.blackwellpublishing.com/), SAGE (https://www.sage.com/en-us/), Frontiers (https://www.frontiersin.org/), PLOS ONE (https://journals.plos.org/plosone/), GoogleScholar (https://scholar.google.com/), MDPI (https://www.mdpi.com/), Scientific Reports (https://www.nature.com/), the Web of Science (https://mjl.clarivate.com/home), the Directorate of Open Access Journals (https://doaj.org/), and African Journal Online (https://www.ajol.info/index.php/ajol). Specifically, the following words, terms, and/or their combinations were looked for in keywords, titles, and abstracts of the articles, i.e., “energy,” “energy resources”, “renewable energy”, “non-renewable energy”, “global energy”, “energy extraction”, “impact of energy extraction”,”

"biodiversity", and "biodiversity and energy", "clean energy'', ''coal'', "coal mining", "nuclear energy", "oil extraction", "natural gas", "wind energy", "solar energy", "hydropower", "bioenergy", "energy and climate change", "fossil fuels", "effects of fossil fuels on biodiversity", "energy and environment", "oil spills", and "wind turbines".

3. The impact of non-renewable energy on biodiversity

The extraction and use of non-renewable energy sources have significant negative environmental impacts, including the emission of greenhouse gases, habitat destruction, and pollution of air and water. These effects harm global biodiversity and contribute to climate change [11,12]. Non-renewable energy sources, such as coal, oil, natural gas, and nuclear energy, are central to industrialization and economic growth. Coal has been a key energy resource for over a century, driving global economic development [13]. However, its environmental consequences are severe, with a particularly detrimental effect on biodiversity and ecosystems [13].

Coal mining activities often involve the large-scale clearing of land, leading to significant habitat loss and the destruction of biodiversity. When open-pit mines and industrial facilities are constructed in areas previously occupied by forests rich in diverse flora and fauna, the local biosphere undergoes drastic alterations. These changes disrupt ecosystems and contribute to the loss of species. Additionally, the expansion of mining operations can hinder natural processes, such as animal reproduction, and create lasting negative impacts on both ecological and archaeological sites [14]. The disturbance caused by mining activities affects both lowland and high-altitude ecosystems, leading to widespread environmental degradation and soil erosion. As a result, species populations fluctuate, with some potentially facing extinction due to habitat loss and disruption. Moreover, the fragmentation of land makes it increasingly difficult to rehabilitate or reforest the areas after mining, further hindering efforts to restore the natural environment [15]. Coal mining can lead to the contamination of both surface and underground water resources, as oxygen exposure significantly degrades water quality. The release of minerals, including heavy metals and sulfates, from coal mines poses a serious threat to aquatic ecosystems and the health of communities living downstream, as these pollutants contaminate water sources [16]. Acid Mine Drainage (AMD) is another significant concern related to coal mining. It occurs when air and water interact with sulfide minerals in coal-bearing rocks, resulting in the release of acidic discharge with a low pH. This acidic runoff can severely pollute rivers and streams, further damaging aquatic ecosystems and water quality [17].

The generation of energy through coal combustion is a major contributor to air pollution. Coal-fired power plants and many industrial facilities release harmful emissions, including sulfur dioxide, nitrogen oxides, carbon dioxide, and various forms of particulate matter, all of which significantly degrade air quality and contribute to environmental harm [12]. All these pollutants have a detrimental impact on the climate. The situation becomes particularly critical as the accumulation of greenhouse gases, such as carbon dioxide, contributes to climate change and global warming. This underscores the urgent need for cleaner and more sustainable energy sources to

mitigate these harmful effects [12]. To use coal as an energy source for sustainable development, it is crucial to consider its impact on global biodiversity and understand the causal relationship between the two. By addressing the negative effects of coal mining and promoting biodiversity protection, we can align ecological integrity with human development, ensuring that both are mutually supportive rather than conflicting [15].

Oil has been the dominant energy source for over a century, fueling global industrial growth and economic expansion. However, its extraction and consumption have caused significant harm to ecosystems, particularly biodiversity, around the world [18]. Oil exploration and drilling activities often lead to habitat destruction and fragmentation. These impacts have catastrophic effects on ecosystems, resulting in the loss of wildlife and biodiversity. The extraction, transmission, and refining of oil release pollutants, including oil spills, which devastate both land and marine ecosystems. The exposure of wildlife to oil spills contributes to a significant decline in species and biodiversity, causing long-term ecological damage and threatening the stability of affected environments [18]. The release of greenhouse gases from burning oil has a detrimental effect on both wildlife and climate, as it contributes significantly to climate change. Altered habitats and disruptions in species' migratory and natural behaviors due to shifting climates can lead to the extinction of vulnerable species, particularly those crucial for maintaining biodiversity, resulting in the overall loss of ecosystem stability [18].

Recognizing the interconnectedness between oil as an energy source and global biodiversity is crucial for developing viable energy solutions. By addressing the environmental impacts of oil extraction, such an approach would lay the foundation for a more sustainable future, helping to mitigate damage to ecosystems and promote long-term ecological balance [18]. Natural gas is increasingly being favored as an energy source over coal and oil, but it still poses significant environmental risks. Composed primarily of methane, natural gas is used for heating, power generation, and as an industrial feedstock. However, its extraction and use have a considerable impact on ecosystems, particularly affecting global biodiversity [19]. Hydraulic fracturing, or the extraction of natural gas through drilling, can cause significant ecosystem disruption. This process leads to habitat destruction, which in turn results in loss of biodiversity and the displacement of wildlife, further damaging the integrity of local ecosystems [20]. The table below illustrates the correlation between the use of energy resources and their impact on global biodiversity (**Table 1**).

Table 1. The relationship between energy resource usage and its impact on global biodiversity.

Energy resource	Impact on environment	Details	Source
Coal	Habitat destruction	Surface mining and mountaintop removal eliminate habitats, leading to biodiversity loss.	[14]
	Air pollution	Coal combustion releases toxic pollutants (SO_2, NO_x, mercury), harming plants, animals, and ecosystems.	[1]
	Climate change	Coal is a major source of greenhouse gas emissions, contributing to global warming and ecosystem disruption.	[1]

Table 1. (*Continued)*.

Energy resource	Impact on environment	Details	Source
Oil	Oil spills	Spills contaminate marine and terrestrial habitats, causing long-term damage to flora and fauna.	[21]
	Habitat fragmentation	Pipeline and drilling operations fragment ecosystems, disrupting wildlife corridors.	[21]
	Air pollution	Combustion emits greenhouse gases and particulates, indirectly affecting biodiversity through climate change.	[22]
Natural Gas	Habitat disturbance	Fracking and drilling activities disturb local habitats and species.	[20]
	Water contamination	Chemicals from fracking can pollute groundwater, affecting aquatic life and terrestrial species reliant on these sources.	[20]
	Methane leaks	Methane emissions contribute to global warming, indirectly impacting biodiversity.	[23]
Nuclear energy	Radiation exposure	Accidents like Chernobyl and Fukushima have caused severe, long-term ecological damage in affected regions.	[24]
	Waste disposal	Poor handling of radioactive waste can contaminate soil and water, affecting biodiversity.	[25]
	Thermal pollution	Discharge of heated water from plants alters aquatic ecosystems.	[26]
Hydropower	Aquatic habitat alteration	Dams disrupt river ecosystems, block fish migration, and change sediment flow.	[27]
	Land use change	Large reservoirs submerge terrestrial habitats, displacing species.	[28]
Solar energy	Land use	Large-scale solar farms fragment habitats and reduce biodiversity.	[29]
	Heat island effect	Panels can create microclimates that affect local species.	[30]
Wind energy	Wildlife collisions	Turbines pose a collision risk to birds and bats.	[31]
	Habitat disturbance	Construction and operation disturb local wildlife, especially during migration and breeding seasons.	[31]
Bioenergy	Deforestation	Large-scale biofuel crop production leads to habitat destruction and reduced biodiversity.	[32]
	Monoculture practices	Growing single-species crops reduces ecosystem complexity and resilience.	[32]

Methane emissions from the extraction and transportation of natural gas contribute significantly to the release of greenhouse gases, which in turn jeopardize the habitats of both resident and migratory species. These emissions exacerbate climate change, leading to a considerable loss of biodiversity [33]. The continued use of natural gas intensifies the ongoing issue of climate change by adding to the greenhouse gas emissions that drive global warming. As the climate alters natural habitats, it disrupts the migration and reproductive patterns of many species, which can trigger abrupt ecosystem changes, further accelerating biodiversity loss and increasing the risk of extinction for certain species [34]. It is essential to understand the interconnections between natural gas as an energy source and biodiversity in order to develop strategies that promote eco-friendly alternatives. By addressing these challenges, we can prevent further biodiversity destruction caused by natural gas production and work toward a more environmentally sustainable future.

Nuclear energy, one of the most powerful resources available for energy production, has the potential to reduce greenhouse gas emissions when utilized efficiently. However, its impact on the global biodiversity crisis is complex and multifaceted, particularly in relation to fossil fuel consumption. The construction and operation of nuclear power stations can lead to habitat fragmentation and degradation. Unlike coal mining, nuclear plants require waste cooling systems and adequate land

for waste storage, which directly alters local ecosystems and negatively affects biodiversity [24]. Furthermore, the biological consequences of nuclear energy generation are concerning. Improper disposal of waste can result in contamination of both land and water, posing significant threats to biodiversity. It is essential that this waste is handled and disposed of properly to mitigate its harmful effects [24]. While nuclear energy produces significantly lower greenhouse gas emissions during operation, the mining, processing, and waste disposal associated with nuclear power contribute to considerable emissions. Since climate change, primarily driven by greenhouse gas emissions, significantly impacts biodiversity by altering environmental conditions that threaten species survival [25], these indirect emissions are still a major concern. It is crucial to understand the relationship between nuclear energy and biodiversity across the globe. By addressing the negative side effects of nuclear energy, we can work toward preserving biodiversity and achieving a more sustainable future. **Table 2** below illustrates the causal relationship between the environmental impacts of non-renewable energy and global biodiversity.

Table 2. Global environmental impacts of non-renewable energy on biodiversity.

Environmental Impact	Causal relationship with global biodiversity	Source
Destruction of habitat	Deforestation, habitat fragmentation, and land degradation result from the extraction of fossil fuels through mining and drilling. As a result, species are displaced and biodiversity is decreased.	[2]
Emissions of greenhouse gases and climate change	Burning fossil fuels creates greenhouse gases like CO_2, which causes global warming. This alters species ranges and habitats, which impacts biodiversity.	[1]
Pollution of the air	Burning fossil fuels releases sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter that harms plant and animal species by causing smog and acid rain.	[35]
Pollution of water	Water pollution from the exploitation of fossil fuels, particularly coal mining, is caused by chemicals and heavy metals. Biodiversity is harmed by this degradation of aquatic ecosystems.	[36]
Acidification of the oceans	Oceans absorb more CO_2 emissions from burning fossil fuels, which causes acidification. Marine ecosystems are harmed by this, especially coral reefs and organisms that create shells.	[37]
Depletion of resources	Important habitats (such as forests and wetlands) are depleted as a result of the extraction of non-renewable resources like coal, oil, and natural gas, which lowers the biodiversity of those ecosystems.	[38]
Species loss	Environmental stress and habitat loss brought on by fossil fuels are major causes of population decreases and extinctions, especially in delicate ecosystems like coral reefs and wetlands.	[39]
Soil erosion	Mining operations, especially those involving coal and oil extraction, destabilize the soil, causing erosion and plant species loss that affects animals in the area.	[15]
Heat-related pollution	Fossil fuel-burning power stations discharge warm water into adjacent rivers or seas, upsetting aquatic life and reducing species diversity.	[26]

4. Effects of renewable energy on biodiversity

Renewable energy sources, when converted into economic resources, play a significant role in determining the growth of countries across continents. However, while the expansion of these energy resources fosters international economic cooperation, it also poses a threat to global biodiversity. Renewable energy sources have both positive and negative implications for biodiversity, due to their complex relationship with the environment.

Solar energy, for instance, has significant potential for reducing global warming. Solar farms in America have contributed to the reduction of carbon dioxide emissions by up to 800 million metric tons [40]. However, the global expansion of solar energy

farms on previously untouched land disrupts various biomes, leading to habitat loss and adverse effects on biodiversity. Solar energy's impact on biodiversity can be either positive or negative, depending on how and where new infrastructure is constructed. Compared to fossil fuels, solar energy generally has a less severe effect on the environment [41]. When solar farms are built on degraded or disturbed land, they can create new habitats and support wildlife, mitigating some of the potential negative effects [42]. Negative impacts of solar energy include habitat loss and alteration due to the large land areas required for solar farms. This can pose risks to wildlife and ecosystems [29]. Additionally, wildlife, such as birds and bats, may suffer from collisions with solar panels, and some animals may be misled by the reflective surfaces [42]. The installation and maintenance of solar farms can also contribute to land erosion, affecting the availability of food and water for wildlife [42].

Wind energy, another renewable resource, generates power through wind and is considered one of the cleanest and most sustainable energy sources, helping to reduce greenhouse gas emissions and combat climate change [43]. Nevertheless, the construction and operation of wind farms can impact global biodiversity in both positive and negative ways. On the positive side, wind energy reduces reliance on fossil fuels, contributing to the fight against climate change, a major threat to biodiversity. By mitigating climate change, wind energy can help protect ecosystems from the harmful effects of temperature fluctuations and habitat loss [44]. Additionally, some wind farms are designed to integrate with the natural environment, providing shelter and habitats for certain species, such as bats and birds [45,46]. On the negative side, wind turbines can lead to bird and bat mortality due to collisions with the rotating blades. This is particularly concerning for species that are already threatened or vulnerable [47]. Research indicates that wind turbines can significantly impact bird and bat populations, especially species that flock or exhibit social behavior [47,48]. Habitat loss and fragmentation are primary concerns when it comes to wind energy facilities [49,50]. Many species are likely to be impacted by the loss and fragmentation of their habitats as a result of the development and maintenance of these projects. Poorly managed wind energy projects can exacerbate these effects, worsening the decline of biodiversity on a global scale [50,27]. Additionally, the noise and vibrations generated by wind turbines can disrupt wildlife migration patterns. These disturbances may hinder species' abilities to find food, breed, or avoid danger, leading to a reduction in population numbers, especially for vulnerable species [48].

Hydropower, a renewable energy source derived from water, offers significant potential in combating climate change by reducing reliance on fossil fuels. However, the construction and operation of hydropower plants can also have both positive and negative effects on global biodiversity [51]. On the positive side, hydropower plays a critical role in mitigating climate change, which poses a significant threat to biodiversity. By reducing fossil fuel consumption, hydropower helps address climate change, one of the most pressing issues affecting ecosystems worldwide. Additionally, some hydropower projects can enhance habitats, as reservoirs provide additional nesting sites for wetland birds and habitats for aquatic species [51]. However, the negative impacts of hydropower cannot be overlooked. The construction and operation of hydropower plants can drastically alter freshwater ecosystems and affect species dependent on these habitats. Changes in water flow, geomorphology, and stream

fragmentation can disrupt the behaviors and migration patterns of both aquatic and terrestrial species [51]. Moreover, the cooler water released from reservoirs can alter the timing of species' migrations and reproductive cycles, as many species rely on specific temperature ranges for these critical life processes. These disruptions can further harm biodiversity and exacerbate the challenges faced by species in changing environments.

Water quality can be negatively affected by the development and operation of hydropower projects, which, in turn, impacts the health of aquatic ecosystems. Pollution and sedimentation caused by these projects can harm fish populations and other aquatic life [52]. During hydropower construction, structural changes in land use occur, such as clearing forests and converting natural habitats into reservoirs. These changes can result in habitat loss and fragmentation, which negatively affects numerous species [28]. Moreover, hydropower projects can unintentionally introduce non-native species into a region, which can outcompete or displace native species, disrupting the local ecosystem. It is critical to address the control of these invasive species to protect biodiversity in areas where hydropower projects are being implemented [51]. On the other hand, bioenergy is an environmentally friendly energy source derived from biomass, which includes wood, agricultural products, and waste from farms, forests, and yards [32]. As a clean and reliable alternative to fossil fuels, bioenergy can contribute to reducing greenhouse gas emissions and mitigating climate change. However, the production and use of bioenergy can also have both positive and negative implications for global biodiversity. **Table 3** shows some examples of the impact of renewable energy on biodiversity.

Table 3. Some examples of the impact of renewable energy on biodiversity.

Renewable energy resource	Environmental impact on biodiversity	Source
Wind power	• Habitat loss and fragmentation: Local animals may be impacted by habitat disturbance caused by wind farm construction. • Collision risks: Bats and birds run the danger of dying in a collision with turbine blades. • Disturbance: The presence of turbines and noise can disrupt the behavior and nesting habits of wildlife.	[44,46,48]
Solar power	• Land use: Huge solar power plants need a lot of land, which might result in habitat loss and fragmentation. • Heat islands: Local plants and animals may be impacted by the local heat islands produced by solar panels. • Chemical use: Chemicals used in the production and disposal of solar panels have the potential to damage ecosystems if improperly handled.	[30,42]
Hydropower	• Habitat alteration: Species that depend on freely flowing rivers are impacted by the changes made to aquatic and terrestrial environments by damming rivers. • Fish migration disruption: Dams have the potential to block fish species' migratory paths, which can have an impact on their life cycles. • Changes in water quality: Aquatic life may be impacted by temperature and oxygen variations brought on by altered water flow.	[51]
Geothermal energy	• Land subsidence: Ground subsidence brought on by the extraction of geothermal fluids may have an impact on nearby ecosystems. • Thermal pollution: Aquatic animals may be impacted by the change in local water temperatures caused by the discharge of spent geothermal fluids. • Chemical emissions: Local biodiversity and air quality may be harmed by the release of gases such as hydrogen sulfide during extraction.	[26]

Table 3. (*Continued*).

Renewable energy resource	Environmental impact on biodiversity	Source
Bioenergy	• Deforestation: The production of bioenergy crops may result in habitat loss due to deforestation. • Monocultures: When single-species bioenergy crops are planted on a large scale, ecosystems are changed, and biodiversity is decreased. • Water use: Growing bioenergy crops can use a lot of water, which might affect dependent species and nearby water supplies.	[32]

5. Case studies illustrating the impacts of renewable and non-renewable energy on biodiversity

Some case studies have shown that non-renewable energy, i.e., coal mining, causes extensive habitat destruction and pollution, leading to species extinction. For instance, mountaintop removal mining in Appalachia, USA, has led to the destruction of habitats critical to species like the eastern hellbender salamander (*Cryptobranchus alleganiensis*), contributing to the decline in biodiversity [53]. Similarly, the Cerrejón coal mine in Colombia has caused severe habitat loss, endangering species such as the jaguar [54] and has impacted indigenous communities. The Adani Carmichael coal mine in Australia threatens species like the bilby (*Macrotis lagotis*) and black-throated finch (*Poephila cincta*) due to habitat degradation [55]. Black Sea coast coal mining in Bulgaria has also caused soil erosion and coastal ecosystem destruction, affecting migratory bird species [56]. Coal mining in Russia's Kuzbass region has caused air and water pollution, damaging local ecosystems and aquatic life [57].

On the other hand, renewable energy projects like wind and solar power can also affect biodiversity, though often in different ways. Wind farms, such as those in the UK, have led to bird and bat fatalities due to collisions with turbines [58]. Similarly, offshore wind farms in the North Sea impact marine ecosystems, though some species benefit from the structures [59]. Solar power projects in ecologically sensitive areas like the Amazon rainforest raise concerns about habitat disruption [60]. These case studies highlight the need for careful planning and mitigation strategies to minimize biodiversity impacts from both energy types. Furthermore, studies estimate that wind turbines killed more than 600,000 bats in the U.S. in 2012, with the greatest mortality occurring in the Appalachian Mountains [61]. Wind turbines are estimated to be responsible for losing less than 0.4 birds per gigawatt-hour (GWh) of electricity generated, compared to over 5 birds per GWh for fossil-fueled power stations [62].

6. Mitigation measures for the impact of renewable and non-renewable energy on biodiversity

To minimize the negative impacts of renewable energy projects on biodiversity, several effective mitigation measures can be employed. One of the most critical strategies is careful site selection. For example, the construction of solar farms in the Mojave Desert in California was designed to avoid fragile ecosystems by placing the farms on previously disturbed land. This careful selection has helped mitigate habitat destruction and maintain biodiversity [63]. Similarly, wind farms in the United Kingdom have been strategically located away from important bird migration routes,

reducing the risk of collisions with wind turbines. Hydropower projects, such as the Three Gorges Dam in China, have incorporated fish passage systems to help aquatic species navigate around dams, minimizing the impact on fish populations [64]. Another key mitigation strategy is the application of the mitigation hierarchy, which involves a sequence of actions: avoidance, minimization, restoration/rehabilitation, and offsetting. A notable example is the mitigation strategy applied in the Amazon rainforest, where solar power plants have been developed with strict protocols to minimize habitat disturbance and avoid ecologically sensitive areas. This careful approach has preserved the integrity of surrounding ecosystems [65]. Furthermore, in areas where damage has occurred, such as wind farms in the United States, rehabilitation efforts have been made to restore native vegetation and wildlife habitats, improving the long-term sustainability of energy development [66].

For non-renewable energy, mitigation measures aim to reduce habitat destruction, pollution, and species displacement associated with energy extraction and production. One example is the case of the Canadian oil sands in Alberta, where significant efforts have been made to implement reclamation strategies after extraction. Reclamation involves replanting vegetation, restoring water courses, and rehabilitating wildlife habitats to minimize the long-term environmental impacts [67]. Similarly, the mining operations in the Democratic Republic of Congo for cobalt and other minerals have raised concerns about biodiversity loss, prompting stricter environmental regulations and the establishment of wildlife corridors to mitigate the fragmentation caused by mining infrastructure [68]. Pollution control technologies are also critical for reducing the environmental harm caused by non-renewable energy extraction. For instance, the coal mines in Wyoming, USA, have employed air scrubbers and wastewater treatment systems to reduce harmful emissions and pollutants released into surrounding ecosystems [69]. Additionally, monitoring and addressing pollution from spills, leaks, and toxic waste in the Niger Delta have become essential to safeguard local biodiversity, as oil extraction in the region has led to extensive damage to coastal and marine ecosystems [70]. Post-extraction habitat restoration and rehabilitation are essential to mitigate biodiversity loss. The UK's post-mining reclamation efforts, where former coal mining sites are being transformed into new wildlife habitats, demonstrate the importance of restoring land to a functional state after resource extraction [71]. **Table 4** provides a succinct summary of the case studies, outlining the type of energy involved, the mitigation strategies implemented, and relevant references.

Table 4. Case studies of energy types and corresponding mitigation strategies implemented.

Case study	Energy type	Mitigation measures	Source
Mojave desert solar program	Renewable energy	Solar farms were constructed on previously disturbed land to minimize ecological disruption.	[63]
Three gorges dam fish passage system	Renewable energy	Fish passage systems are integrated into hydropower projects to allow aquatic species to bypass the dam.	[64]
Amazon solar power plants	Renewable energy	Solar power plants developed with strict protocols to avoid ecologically sensitive areas in the Amazon rainforest.	[65]
Wind farms in the UK	Renewable energy	Wind farms are strategically located away from bird migration routes to reduce collision risk.	[66]

Table 4. (*Continued*).

Case study	Energy type	Mitigation measures	Source
Oil sands reclamation in Canada	Non-renewable energy	Post-extraction reclamation involves replanting vegetation, restoring water courses, and rehabilitating wildlife habitats.	[67]
Cobalt mining in the Democratic Republic of Congo	Non-renewable energy	Implementing stricter environmental regulations, including wildlife corridors to mitigate habitat fragmentation caused by mining infrastructure.	[68]
Wyoming coal mines carbon capture technology	Non-renewable energy	Air scrubbers and wastewater treatment systems to reduce harmful emissions and pollutants.	[69]
Niger delta oil extraction	Non-renewable energy	Monitoring and cleaning up spills and waste, along with restoring coastal and marine ecosystems, to reduce environmental damage.	[70]
UK post-mining reclamation efforts	Non-renewable energy	Rehabilitating former coal mines by transforming them into wildlife habitats and restoring natural landscapes.	[71]

7. Conclusion

Economic development has long relied on non-renewable resources like gas, oil, and coal, contributing to environmental degradation, including climate change, pollution, and habitat destruction. This has led to a significant decline in biodiversity, with many species at risk of extinction. While renewable resources such as solar, wind, and hydropower reduce greenhouse gas emissions and mitigate climate change, they also pose biodiversity risks. For example, wind turbines can harm bird and bat populations, and large solar farms can disrupt ecosystems. To address these challenges, it is crucial to prioritize careful planning and mitigate the negative impacts of energy production on biodiversity. Implementing an integrated energy approach that minimizes conflicts between energy generation and biodiversity conservation is essential. This includes engaging local communities, investors, and governments while conducting thorough environmental impact assessments prior to project implementation. Investing in technological innovation through research and development can also improve the environmental performance of both renewable and non-renewable energy sources. By understanding the different impacts of these energy types on biodiversity, we can develop effective mitigation strategies that lead to a more sustainable and balanced future.

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