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Article

Exploring the link between energy resources and global biodiversity

Joseph Matwani[1,*], Fredrick Ojija[2]

[1] Department of Electrical and Power Engineering, College of Engineering and Technology, Mbeya University of Science and Technology, P.O. Box 131, Mbeya, Tanzania
[2] Department of Earth Sciences, College of Science and Technical Education, Mbeya University of Science and Technology, P.O. Box 131, Mbeya, Tanzania
*** Corresponding author:** Joseph Matwani, josephmatwani@gmail.com

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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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Article

Geographical indications in Indian agriculture products: A pathway to sustainability and social development

Vikas Kumar

Indian Institute of Information Technology Vadodara-International Campus Diu, Diu 362520, India; vikas_kumar@diu.iiitvadodara.ac.in

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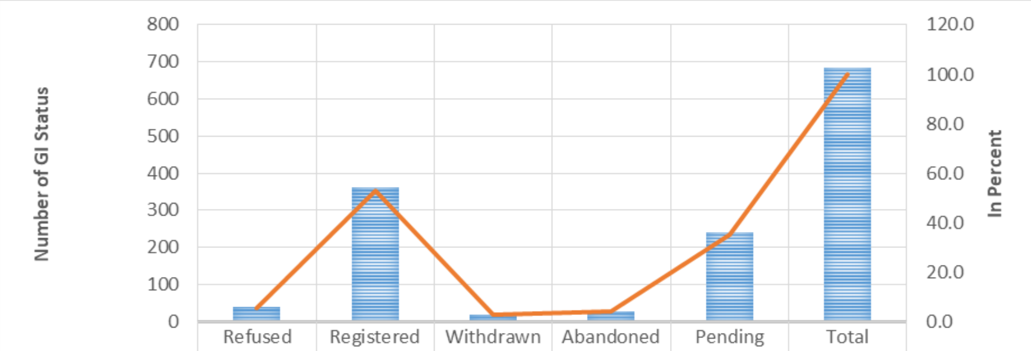
Abstract: Geographical Indications (GIs) are one of the important types of Intellectual Property Rights (IPRs) that are based on the geographical region. In light of this, the geographical region is vital for innovation to develop the regional economy and significant to understanding innovative performance in the particular region. With this context, the objectives of the paper are 1) to assess GIs products and sketch the historical development of GI in India; 2) to explore the scenario of agriculture products registered under the GIs; and 3) to address challenges of GIs during registration. Furthermore, the study is based on secondary data obtained from the Geographical Indication Registry of India. Findings: The study shows that the number of agricultural product registrations has increased in the last few years. This increase may be attributed to the new IPR policy regime and heightened public awareness.

Keywords: geographical indications; agriculture; IPR; policy; India

1. Introduction

The new Intellectual Property Rights were introduced in the year 2016 in India. The policy focused on creating public awareness about the economic, social, and cultural benefits of IPRs among all sections of society. It lays down the seven objectives: 1) IPR awareness; 2) generation of IPR; 3) legal and legislative framework; 4) administrative and management; 5) commercialization of IPR; 6) enforcement and adjudication; and 7) human capital development [1]. The impact is evident in India's ranking in the Global Intellectual Property Index, where it ranked 40th out of 53 countries. Although IPR scores jumped 2.42%, increasing from 36.04% (16.22 out of 45) in 2019 to 38.46% (19.23 out of 50) in 2020 [2].

The Indian government has made a focused effort to support investments in innovation and creativity through increasingly robust IP protection and enforcement. In this context, Geographical Indications (GIs) have been becoming one of the important tools to identify and protect regionally based products. However, GI products also have certain characteristics based on the manufacturing skills and traditions of a particular place of origin. For instance, Bnarasi Saree is handmade using local natural resources and is usually embedded in the traditions of local communities [3]. GI has been separated into five categories (i.e., Handicraft (including Textiles), Agricultural, Manufactured, Foodstuff, and Natural). The Registry started the registration process on 15th September 2003, and till now, 685 applications have been received, as shown in **Figure 1**.



	Refused	Registered	Withdrawn	Abandoned	Pending	Total
Number	38	361	19	27	240	685
Percentage	5.5	52.7	2.8	3.9	35.0	100

Figure 1. Status of geographical indication in India since 2004–2020.

Source: Calculated from the Geographical Indication Registry, 2025.

The figure above shows the total GI application received and out of 685, almost 53% of the application registered, and 35% of the applications are still pending. Besides this, almost 3% of the applications were withdrawn, also 5% and 4% of the applications were refused and abandoned respectively. However, now the registry has been more focused on conducting awareness programs in India to promote the registration of GIs. These areas are being focused on tea, coffee, spices, agriculture and horticulture products, handloom products, handicrafts, textiles, processed food items, dairy products, natural goods, spirits, and wines.

Further, agricultural products have qualities that belong to the specific region and geographical factors (i.e., climate and soil). It may be one of the reasons that most GI products are registered under agricultural products and foodstuffs. Broadly, this category of product has a specific geographical origin and possesses qualities or a reputation that has assigned a unique sign or logo. The qualities of the product depend on the geographical place of production, such as litchi from Muzaffarpur in Bihar, India. It is thus necessary to assess the status of GI products, especially agricultural products, in India. In light of this, the objectives of the paper are 1) to assess GIs products and sketch the historical development of GI in India; 2) to explore the scenario of agricultural products registered under the GIs; and 3) challenges of GIs during registration. In addition to this, the paper has been categorized into a different section to fulfill the objectives. In this regard, contextualizing the legal framework of GI and the historical development of GI in India is discussed in the second section. This is followed by a detailed discussion on the pattern of agricultural products protected so far under GI. The succeeding section discusses the issues and challenges of GI, especially for agricultural products. The last concludes the argument.

2. Geographical Indications: Concept and framework

In the 19th century, GI was started in Europe, and it is one of the elements of Trade-Related Intellectual Property Rights (TRIPS) of the World Trade Organization (WTO). In the international framework, it is mentioned in Article 22 of the TRIPS agreement, which directs member countries to provide for the protection of all GI. On the other side, members should provide the ‘legal means for interested parties to secure the protection of their GIs’. According to Article 22 of TRIPS, GI is indications which identify a good as originating in the territory of a member, or a region or locality in that territory, where a given quality, reputation, or other characteristics of the good is essentially attributable to its geographical origin [3]. The development of GI can be traced to the three international conventions, namely the Paris Convention, the Madrid Agreement, and the Lisbon Agreement [4], shown in **Figure 2**.

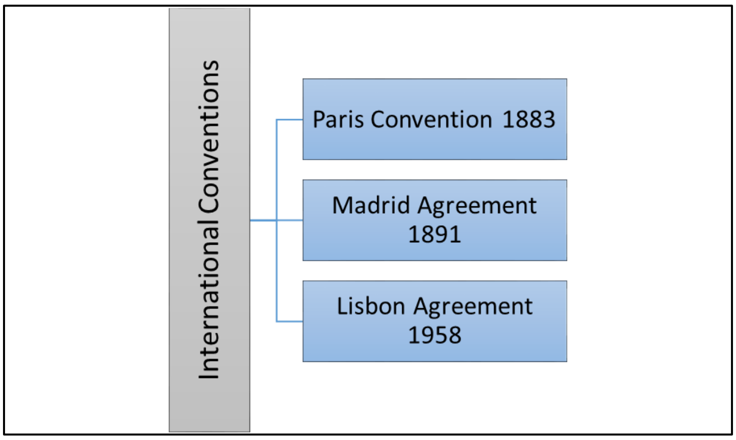


Figure 2. Development of Geographical Indications.

Source: Developed by author, 2025 based on the literature.

The Paris Convention for the Protection of Industrial Property (1883), the Madrid Agreement for the Repression of False or Deceptive Indications of Source of Goods (1891), and the Lisbon Agreement for the Protection of Appellations of Origin and their International Registration (1958). The first two, the Paris Convention and Madrid Agreement**,** raise the "indications of source" and the Lisbon Agreement refers to "appellations of origin" as objects of industrial property [3]. Further, the 'indication of Source' reflects an indication of the origin of the product from a region or country (i.e., Make in India, Made in Japan, or Product of France, etc.). These indications do not show the quality of the product but refer to its origin. On the other hand, "Appellation of Origin" reflects a sign that specifies that a product is in a specific geographical place only when the characteristic qualities of the product are due to the geographical environment, including natural and human factors [5].

Similarly, India joined as a member state of the TRIPS Agreement, a sui generis legislation for the protection of Geographical Indications. This Geographical Indication Act was passed in the parliament in the year 1999 and the Geographical Indications of Goods (Registration and Protection) Rules, 2002, came into force in the year 2003 [5]. Broadly, there were three objectives behind the Geographical Indications of Goods (Registration and Protection) Act, 1999 passed, first, "it is a specific norm in the country that could effectively protect the interest of producers of such products; second, to protect from illegal persons from misusing Geographical Indications and save consumers from deception; and finally, to promote products bearing Indian Geographical Indications in the export market" [4].

GIs are Intellectual Property Rights, that are farmer-friendly and mitigate information asymmetry in agri-food transactions by providing consumers with origin and quality information [5]. GI protection is intended for a group of persons residing in a locality using the name (title). It is the reputation of the product based on its quality that is attained due to geographical factors and prolonged use that makes a GI different from a trademark [6]. GIs provide uniqueness to the product while preserving the authenticity and increasing the market value; they find a way to sustainable farming, increase local employment, and prevent counterfeiting. They also stated that GI-tagged products have higher economic value domestically and internationally [7]. The GIs also boost local tourism and employment opportunities, supporting economic growth [8]. GI in India can be divided into three basic categories: Agri-food, natural commodities, handicrafts, and/or industrial items [9].

According to the UN Food and Agriculture Organization's 2014 report on GIs: "Adding Value to Agricultural Products, the market share of Cognac brandy was only 1% of global brandy sales in 1960, but exceeded 50% by 2014". In another report from the French Ministry of Agriculture in 2014, it is estimated that the production and sales of Roquefort blue cheese could help generate around 500 formal job positions in the Aveyron region. In economics, GIs are considered to promote rural development mainly through two mechanisms—reducing information asymmetry and enabling a degree of monopoly power for producers. While countries like France and Italy have a GI system well established and benefits small farmers, India faces awareness and legal challenges [10].

GI-labeled tea and rice in China have considerable economic profits for local producers [11]. European nations have gained from GI-tagged cheeses and wine, substantial enough to stand in global markets. Talking about India, Tea from Darjeeling and Basmati Rice are internationally recognized, but economic benefits vary due to legal challenges and marketing [12]. GI faces several challenges too, as unawareness, localities, and farmers are unaware of the economic potential of GI identification. Forged and mislabelled products in the market, declining the authenticity. Indian GI products lag behind in global competition due to trade regulations and branding issues [13].

Further, the Geographical Indication Registry was established in 2003 in Chennai, India, to regulate GI products and conduct awareness programs to promote the registration of GIs. It focused on products like tea, coffee, spices, agricultural products, handloom products, handicrafts, textiles, processed food items, dairy products, natural goods, spirits, and wines. With this context, the Registrar of Geographical Indication is categorized into two sections, i.e., Part 'A' which includes particulars relating to registered Geographical Indications, and Part 'B' which refers to particulars of the registered authorized users [14]. The registration process is shown in the **Figure 3** given below:

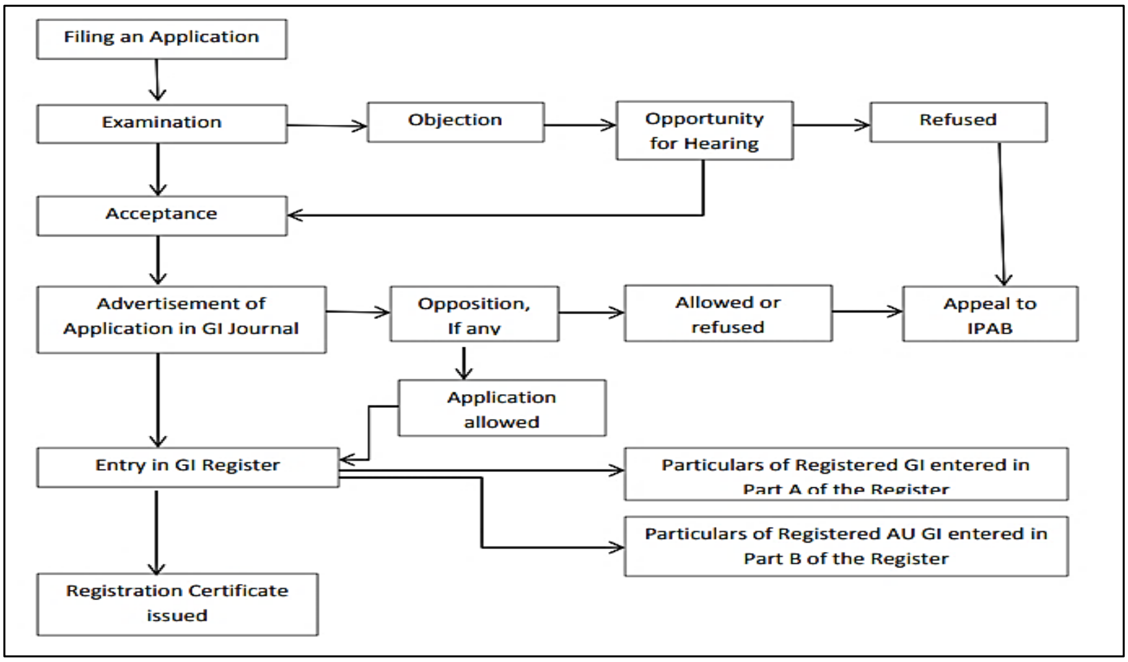


Figure 3. GI registration process under the GI Act 1999 in India.
Source: Geographical Indications Registry, 2020.

The figure above shows the registration process of GI products as per the norms of IPR. The registration of products can be applied by any association of persons, producers, organizations, or authority established by or under the law. The applicant must represent the interests of the producers. The application should be in writing in the prescribed form and addressed to the Registrar of Geographical Indications along with a prescribed fee. Hence, the next section analyzes the pattern of registered agricultural products.

3. Methods

The approach of research is exploratory. It compares the categories of the product and their origin of GI products. In addition, the work maps the sources of GI products, especially agricultural products. This research consists of a comparison between agricultural products and other GI products. The data was collected from the Geographical Indications Registry and descriptive statistics analysis such as frequency tables, bar charts, pie charts, and percentages was used to summarize the result. The period of the data collected was from 2004 to 2020. The period was chosen for analysis because it was established in 2003 to regulate GI products and conduct awareness programs for registering GIs. Besides this, literature, articles, and government reports were also accessed to understand the agricultural GI products and how policy influences innovation in the region. The analysis consists of four parts. Firstly, the agriculture GI products and their contribution to the total GI registered; secondly, the state-wise contribution of agriculture products and other GI products registered; thirdly, the year-wise trend of agriculture products; and fourthly, the issues related to agricultural GI products are discussed. In addition to this, through regression analysis between the government budget and agricultural products. The prediction graph for Random Forest Regression displays a strong correspondence between the predicted and actual data points. It also achieves an R^2 score of 0.8710, demonstrating strong predictive power.

4. Result and discussion: GIs product registered

There was a total of 361 products registered under the GI Protection Act till March 2020. Out of this, 109 GI products were related to agriculture, and 208 GI products were related to handicrafts. Similarly, other types are manufacturing, foodstuff, and natural; the numbers of registered products under these categories are 24, 18, and 2, respectively. On the other hand, it can be seen from the figure given below that 57% of GI products are registered under the types of handicrafts, including textiles, and 30% are registered under agriculture. The rest of the types, such as manufactured, foodstuff, and natural, are 6, almost 5, and less than 1% registered accordingly. The details are shown in the **Figure 4** below.

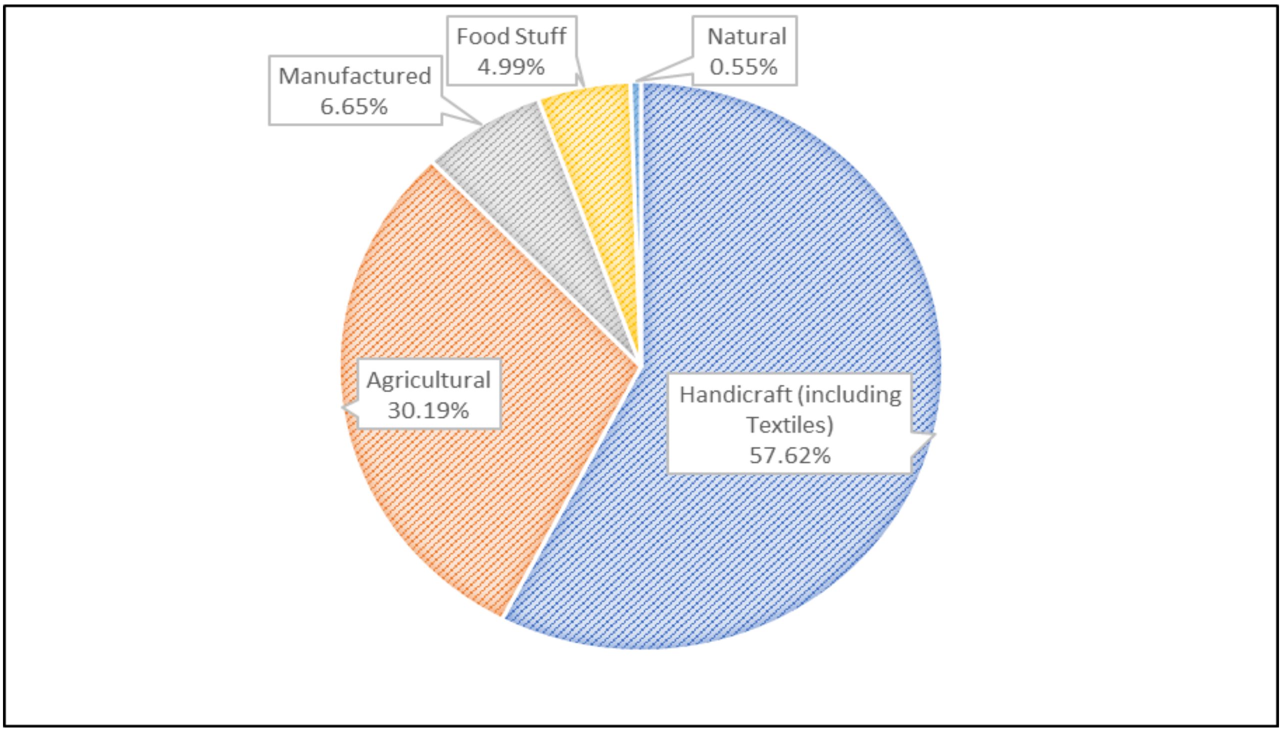


Figure 4. Percentage-wise GI products registered in India till March 2020.

Source: Author compilation from GI Registry, 2020.

4.1. Agriculture products registered under the GIs

There is a total of 361 GI products registered from 2004 to 2020. It is interesting to see the effects of the new IPR policy 2016, and data indicates that agriculture-related products are highly registered. This may be due to the effect of the awareness program run by the Government of India. It can be seen from the table given below that the highest number of agriculture products registered is 14 in the years 2016–2017 and 2018–2019. However, the registered number of agricultural products is continuously increasing. For instance, in the year 2004–2005, the number of Agriculture products is 1 and till March 2020, it is 6, as shown in **Table 1**.

Table 1. Number of agriculture products out of total GI products.

Year	Number of Agriculture-Related Registered GI	Total Number of Register Products under GI	Percentage of Agriculture Registered out of Total GI Products
2004–2005	1	3	33.33
2005–2006	2	24	8.33
2006–2007	2	3	66.67
2007–2008	11	31	35.48
2008–2009	10	45	22.22
2009–2010	5	14	35.71
2010–2011	7	29	24.14
2011–2012	4	23	17.39
2012–2013	2	21	9.52
2013–2014	4	22	18.18
2014–2015	11	20	55.00
2015–2016	9	26	34.62
2016–2017	14	33	42.42
2017–2018	7	26	26.92
2018–2019	14	23	60.87
2019–2020	6	18	33.33
Total	109	361	30.19

Source: Author compilation from GI Registry, 2020.

On the other side, the percentage of registered agriculture products out of the total is shown separately in the figure given below. It can be observed from the figure, and maybe it can be said that, after the new IPR policy regime, the contribution of agricultural products is increasing. For instance, in the year 2018–2019, it increased to almost 61% from nearly 27% in the year 2017–2018. Further, a total of 30% of agriculture products contributed to the total GI registered. In the year 2006–2007, it shows a high percentage because in that particular year, only 3 GI products were registered, and of these, 2 products are agriculture-related. It can be seen in **Figure 5**.

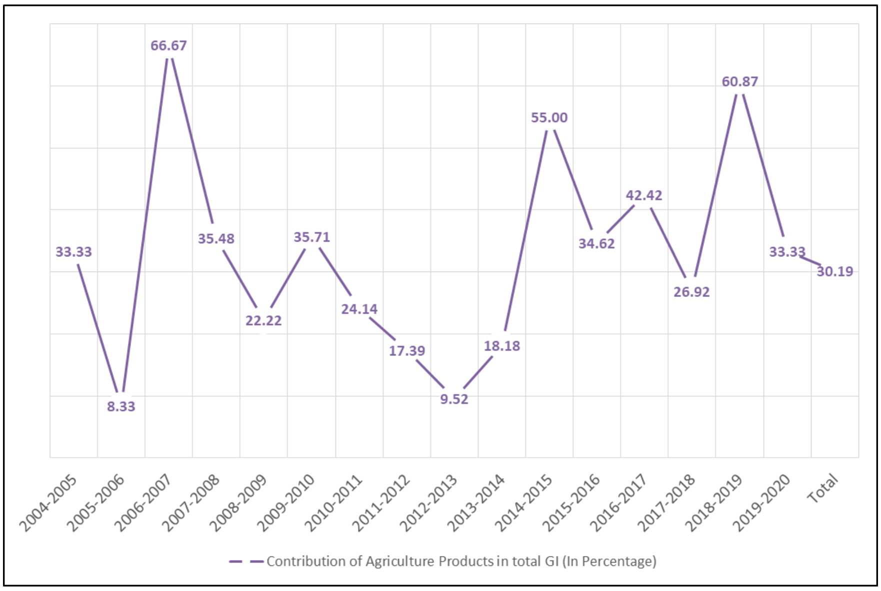


Figure 5. Percentage of agriculture products contribution in total GI registered products from April 2004–March 2020.

Source: Author compilation from GI Registry, 2020.

4.2. State-wise agriculture products registered under GI products

It is important to see state-wise registration of the product. It covered the different states of India and other foreign countries. In the **Table 2**, it can be seen that 346 products were registered from Indian states, and 15 GI products were registered from foreign countries. Out of 346, 109 products belong to the agriculture registered. In the view of agriculture products, the highest number of registered product states are Maharashtra, Karnataka, and Kerala, i.e., 24, 17, and 13, respectively. On the other hand, other states such as J&K, Madhya Pradesh, and Rajasthan do not have any registration-related agriculture GI products. Therefore, it is necessary to pay attention to these states and make more awareness programs related to agriculture.

Table 2. Regional contribution of agriculture products and other GI products registered under the GI Act from April 2004–March 2020.

State	Number of Agriculture-Related Registered GI	Total Number of Register Products under GI	Percentage of Agriculture products Registered out of total GI Products
Andhra Pradesh	2	18	11.11
Arunachal Pradesh	1	2	50.00
Assam	6	8	75.00
Bihar	4	13	30.77
Chhattisgarh	1	6	16.67
Goa	1	2	50.00
Gujarat	2	15	13.33
Himachal Pradesh	2	8	25.00
International	0	15	0.00
Jammu&Kashmir	0	7	0.00

Table 2. (*Continued*).

State	Number of Agriculture-Related Registered GI	Total Number of Register Products under GI	Percentage of Agriculture products Registered out of total GI Products
Karnataka	17	41	41.46
Kerala	13	28	46.43
Madhya Pradesh	0	10	0.00
Maharashtra	24	30	80.00
Manipur	1	4	25.00
Meghalaya	2	2	100.00
Mizoram	1	6	16.67
Nagaland	2	3	66.67
Odisha	2	17	11.76
Pondicherry	0	2	0.00
Rajasthan	0	14	0.00
Sikkim	1	1	100.00
Tamil Nadu	8	35	22.86
Telangana	0	14	0.00
Tripura	1	1	100.00
Uttar Pradesh	3	26	11.54
Uttarakhand	1	1	100.00
West Bengal	6	21	28.57
India	8	11	72.73
Total	109	361	30.19

Source: Author compilation from GI Registry, 2020.
Note: Here in the table, India means those products that are shared and registered by two or more than two states, and international means those that are registered by foreign countries.

On the other hand, the states like Maharashtra, Assam, and Nagaland are the highest contributors. For instance, Maharashtra contributes 80%, Assam contributes 75%, and Nagaland contributes 66%. Similarly, other states like Kerala and Karnataka contribute 46% and 41%. However, those states represent 100% because there is only one GI product, and that is also in agriculture products. There are other states, such as Uttar Pradesh, Andhra Pradesh, Orissa, etc., that have a lower contribution, but these states have other GI products. It can be seen in **Figure 6**.

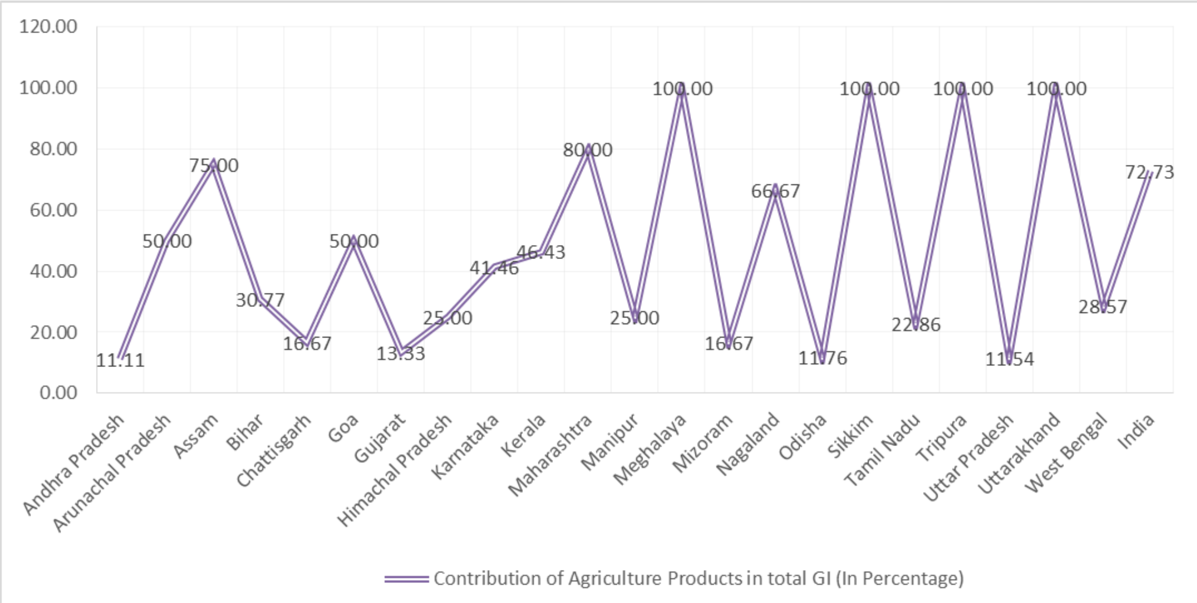


Figure 6. Contribution of agriculture products to the total GI registered by the state from April 2004–March 2020.

Source: Author compilation from GI Registry, 2020. Note: The total of 109 takes into consideration only those States that have registered some agricultural products with GI. Some States have no agricultural products registered with GI. If those States are included the total goes up to 361. It may be noted that this total excludes foreign products registered with GI Registry. Here in the figure, India means those products that are shared and registered by two or more states.

4.3. Trend of agriculture products registered

The trend analysis only shows the agriculture products registered under the GI Act by the states. It has been categorized into 4 series to check the effect of the new IPR regime and other associated programs in the states. It can be observed from the **Table 3** that, from 2016 to 2020, most of the states have registered their agriculture products. During the period of 2016–2020, states like Maharashtra, Karnataka, Kerala, Assam, and Bihar took more initiatives in GI registration, especially agriculture products. Further, there are some other states also that have taken initiatives and registered at least one agriculture-related product. This may be due to the awareness and participation of other stakeholders.

Table 3. Trend of agriculture products registered under GI Acts.

State	Year			
	2004–2008	2008–2012	2012–2016	2016–2020
Andhra Pradesh		1		
Arunachal Pradesh			1	
Assam		1	2	3
Bihar				4
Chhattisgarh				1
Goa				1
Gujarat		2		
Himachal Pradesh	1			1
Karnataka	7	5	2	5
Kerala	2	5	2	4

Table 3. (*Continued*).

State	Year			
	2004–2008	2008–2012	2012–2016	2016–2020
Maharashtra		2	8	14
Manipur			1	
Meghalaya			2	
Mizoram			1	
Nagaland		1	1	
Odisha		1		1
Sikkim			1	
Tamil Nadu		4	1	2
Tripura			1	
Uttar Pradesh	1	1	1	
Uttarakhand				1
West Bengal	1	3		2
India	4		2	2
Total	16	26	26	41

Source: Author compilation from GI Registry, 2020. Note: The total of 109 takes into consideration only those States that have registered some agricultural products with GI. Some States have no agricultural products registered with GI. If those States are included the total goes up to 361. It may be noted that this total excludes foreign products registered with GI Registry. Here in the table, India means those products that are shared and registered by two or more than two states.

On the other hand, a total of 109 agriculture products have been registered from 2004 to 2020, and Maharashtra contributes 22% of agriculture products registered as GI, which is higher than any other state. Similarly, the states such as Chhattisgarh, Goa, Uttar Pradesh, etc., have registered below 1%. The details are shown in **Figure 7**.

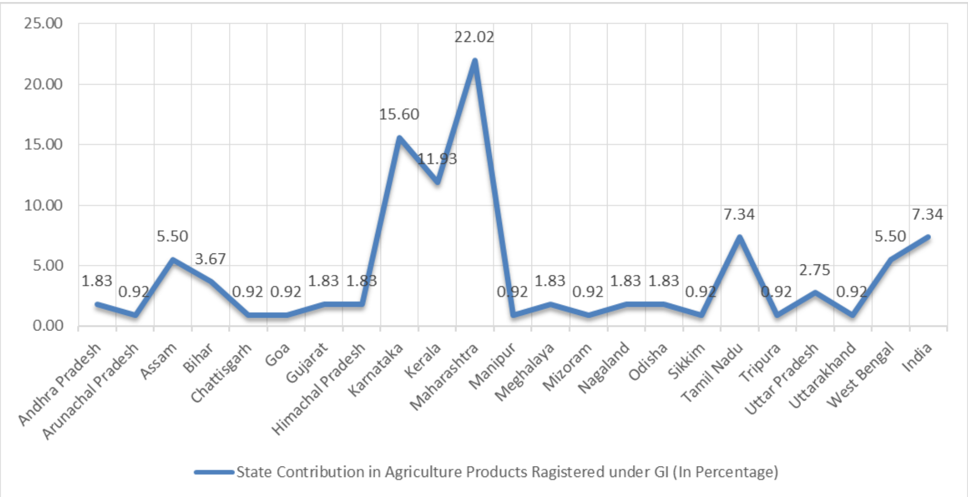


Figure 7. Overall contribution of the state in total agriculture-related products.

Source: Author compilation from GI Registry, 2020. Note: The total of 109 takes into consideration only those States that have registered some agricultural products with GI. Some States have no agricultural products registered with GI. If those States are included the total goes up to 361. It may be noted that this total excludes foreign products registered with GI Registry. Here in the figure, India means those products that are shared and registered by two or more states.

Relationship between agriculture union budget and agricultural GIs products

The prediction graph for Random Forest Regression displays a strong correspondence between the predicted and actual data points, with minimal prediction errors. This indicates that the model effectively captures the relationship between the budget and the number of registered GIs, showcasing its reliability in regression tasks. The details can be seen in **Figure 8**.

Figure 8. Random Forest Regression: Budget vs. registered agricultural GIs products.

Source: Author, 2025.

The Random Forest Regression model achieves an R^2 score of 0.8710, demonstrating strong predictive power. It performs exceptionally well in both regression and classification tasks, but the confusion metrics indicate the potential for improvement in classifying boundary cases through further parameter optimization or feature engineering. The details are shown in **Figure 9**.

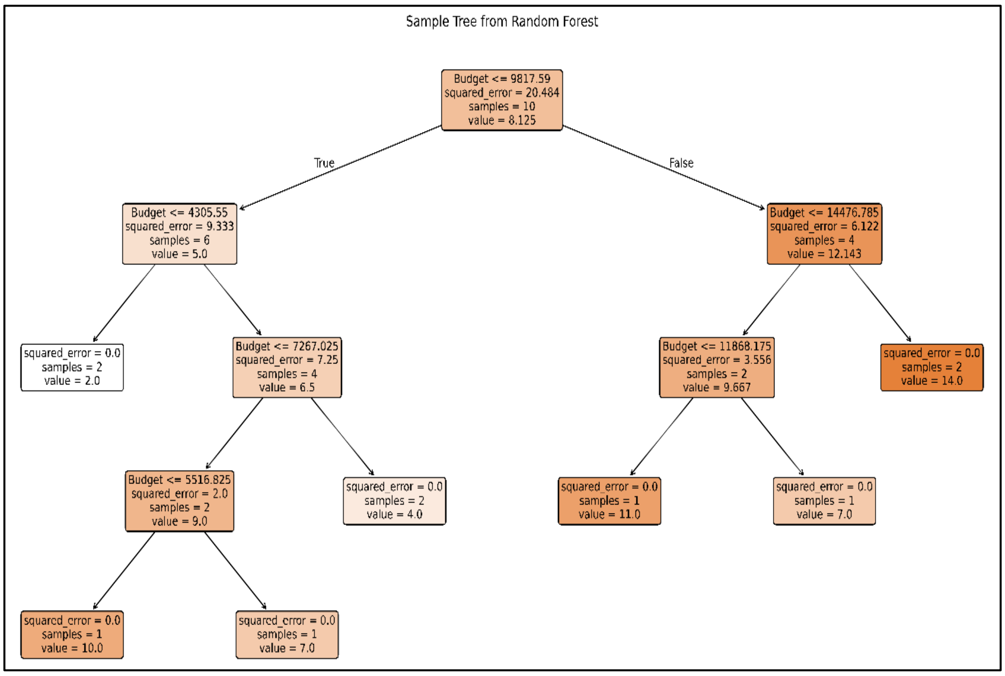


Figure 9. Sample tree from random forest.

Source: Author, 2025.

The confusion matrix reveals an overall accuracy of 81.25%, with precise classification in the “Low (0–5)” and “High (10+)” categories, while some misclassifications occur in the “Medium (5–10)” range. This suggests that the model is consistent but could benefit from fine-tuning to reduce errors in overlapping bins. The details are shown in **Figure 10**.

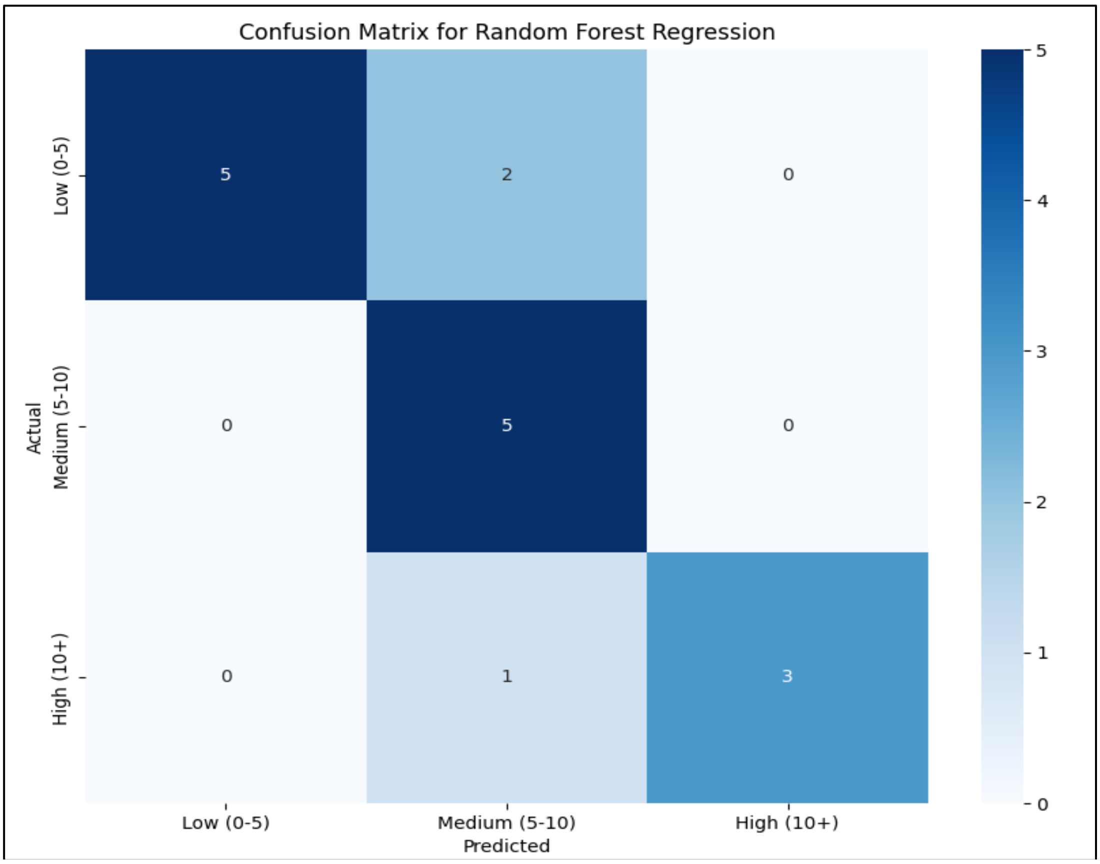


Figure 10. Confusion matrix for Random Forest Regression.

Source: Author, 2025.

5. Issues of agricultural GI products

The registration of agriculture products under the GI Act helps to enhance income as an incentive for individual farmers or institutions. Despite this fact, there are some issues and challenges, i.e., GI logo, awareness, file processing, etc., which need to be tackled. However, these issues may vary from region to region and product to product.

5.1. Commercialization of products

The commercialization of GI products is one of the major issues, especially for agriculture products. According to Naidu [15] not all harvested products are necessary to export; only a certain quantity of product is liable to export. Therefore, the rest of the quantity is sold in the domestic market only. In this context, farmers do not get the benefit as much as they can because of the difference in price between the domestic and international markets [16].

5.2. Lengthy file processing and awareness of the norms

The new IPR Policy 2016 mentioned the lack of awareness and the perception that IP protection is either not required or that the process to obtain it is unnecessarily complicated [5]. As it is known, to register the product, several processes go through various steps that are very complex for a farmer or any layperson. Therefore, because of the complexity, the farmers or institutions have less interest in getting into the process. In addition to this, some farmers are not aware of the norms because of less education. Hence, there is also a need to be concerned about those states where the education level is low. An empirical study conducted in Tamil Nadu and also stated that most of the producers of agricultural and food products (47.97%) have a low level of awareness about GI and its associated benefits [17].

5.3. Identification of GI products

The symbol of the GI product is not equal or common in India; it varies from region to region. Therefore, it is difficult for consumers to identify GI products. In this context, Lalitha and Vinayan [17] argued that despite more than one decade of the Act, there is still a lack of a common logo for all GI products, which affects the awareness of its importance. For instance, another country like Thailand has one common logo, which is easily known by consumers as an indicator of quality and uniqueness [18]. The policy at various levels should focus on IP protection of agriculture products that help in investment and publication and can play a key role in the public domain or awareness about the product [19].

6. Conclusion

India is a country where agriculture is playing an important role in the economy. With this context, geographical indication products, especially agricultural products registered under GI, will boost the economy directly or indirectly. However, it is not intended to argue whether GI is boosting the agriculture sector or not, but based on the data, it can be stated that the registration of products is increasing, especially for agriculture-related. For instance, 30% of agriculture products are registered under GI. Since 2016, the number of products related to agriculture has almost doubled; it has increased up to 41 in 2016–2020 from 26 in 2012–2016. This may be due to government initiatives and programs like Creative and Innovative India, Make in India, etc. However, it has some hurdles, such as the GI logo, file processing, or commercialization of products that need to be tackled. In this sense, there is a need to focus on each state to recognize their unique products in agriculture because, as a data concern, there are few states like Madhya Pradesh, Jammu, Kashmir, Telangana, etc. with still no agriculture products registered under GI.

Conflict of interest: The author declares no conflict of interest.

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Article

Difference-in-difference analysis: The EU integration's effect on quality of life through selected economic security indicators from 2005–2022

Hayriye Hilal Bağlıtaş*, Hayriye Atik

Department of Economics, Faculty of EAS, Erciyes University, Kayseri 38130, Turkey
*** Corresponding author:** Hayriye Hilal Bağlıtaş, hhilalbaglitas@erciyes.edu.tr

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Abstract: Quality of life indicators are significant tools to evaluate the individual's well-being. In this sense, economic security measurement is a part of well-being. In achieving a greater level of well-being, countries can get many benefits by joining economic integrations. However, these benefits may not only sometimes be as great as thought. We investigate the changes in (in)security measurements for the new members with the difference-in-difference method. This method is beneficial for analyzing the effects before and after treatment, policy, and implications for different units. Our study aims to detect if there are significant changes or improvements in the security levels of new members of the European Union from 2005 to 2022. The findings figure out that the level of *arrears* was essentially reduced for most members. Still, the integration has no visible impact on *purchasing power parity* for the period. These are critical findings showing a trend not sourced from integration and, at the same time, the inefficiency of policy and implementation of the EU.

Keywords: economic security; difference-in-difference; quality of life; purchasing power parity; *arrears*

1. Introduction

Indicators of quality of life have 8 + 1 dimensions as "material living conditions, productive activity, health, education, leisure and social interactions, economic and physical security, basic rights, living environment, and overall experience of life". Well-being includes all eight dimensions except the last, which is related to personal life satisfaction and success of well-being [1]. While well-being is a more comprehensive concept than income-related measurements and economic security. Economic well-being is a sub-index of economic security [2]. In this context, various studies of Osberg and Sharpe [2–4] focused on the economic (in)security perspective.

After the Cold War, traditional security studies gave way to non-traditional security (NTS) discourses. These studies were beyond the military forces and closely connected to various anxieties about the welfare and safety of individuals. In this regard, human security has a dissimilar concept compared to the NTS, consisting of the dynamics and struggles of daily life and having a definition depending on a specific unit, such as food security, economic security, health security, environmental security, and political security [5]. Following the financial crisis in the late 2000s, millions of people in OECD countries faced significant economic turmoil, including unemployment, income volatility, and sharp declines in various assets. In a word, the crisis made the people more concerned about their "economic security (ES)" and the extent to which they are vulnerable to economic losses that cause hardship. This growing concern has affected everything from consumer and investment decisions to choices about family formation and geographic mobility to political behavior [6].

It is not similar or homogeneous for all individuals since ES differentiates according to socio-economic characteristics, geography, and age with a wide spectrum [5]. Richiardi and He [7] state that there is no consensus on meaning and measurement, unlike poverty or inequality. However, they give that the definition has two parts; one is related to material source sufficiency [8], and the other is about having feelings about this [7]. Hacker [6] insists that ES is closely related to sensitivity to economic loss, and the security considers the consequences of the loss, not the cause. Furthermore, ES has objective and subjective dimensions such as physical and perceived economic security measurements. Perceived economic security focuses on the psychological response to financial risk and insufficient material sources. Unexpected incidents like unemployment, diseases, and divorces cause a reduction in income and are connected to physical/objective economic security [9]. Hacker [6] classifies the objective measurement ES based on four properties: Financial buffers, shock probabilities, security indexes, and economic (in) stability changes and subjective ES is a kind of reaction or perception to changes in objective ES [2].

On the (in)security side, we have mainly focused on new members since 2004 in the EU. These members are Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, and Slovenia. Because these countries recently joined the EU, most are relatively less affluent than other members. When we use difference-in-difference (DID) estimators, we employ two variables. One variable is *arrears* for the insecurity, and another is purchasing power parity for the security.

Arrears (mortgage or rent, utility bills, or hire purchases) increased in 2021 concerning 2020 with 2.4 and the last decade with 8.3. However, one in three people (30.1%) must face and cannot afford to pay these financial expenses in the EU in **Figure 1**:

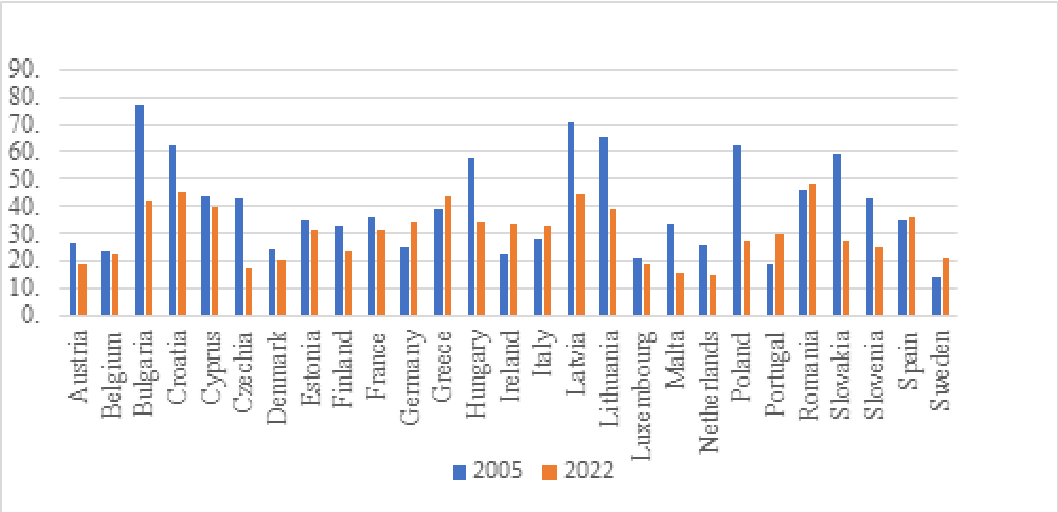

Figure 1. Share of the population unable to face unexpected financial expenses, % of total population [10].

The first values for Romania and Croatia are in 2007 and 2010, respectively.

When we compare 2005 and 2022, this seventeen-year period shows a significant reduction in the rate of inability to meet unexpected financial expenses. Bulgaria, Croatia, Cyprus, Hungary, Latvia, Lithuania, and Poland have the highest level of insecurity rates between 50% and 80%, while Czechia, Estonia, Malta, Slovakia, and Slovenia have an insecurity level of approximately 30%–40% in 2005. The highest rate of countries gained a significant achievement, especially for Bulgaria, Hungary, Latvia, and Lithuania. In the lowest countries, Slovakia and Slovenia have lived appreciable success in diminishing insecurity rates. On the security side, purchasing power parity is a proxy for security analysis. **Figure 2** illustrates *PPP* for 2005 and 2022:

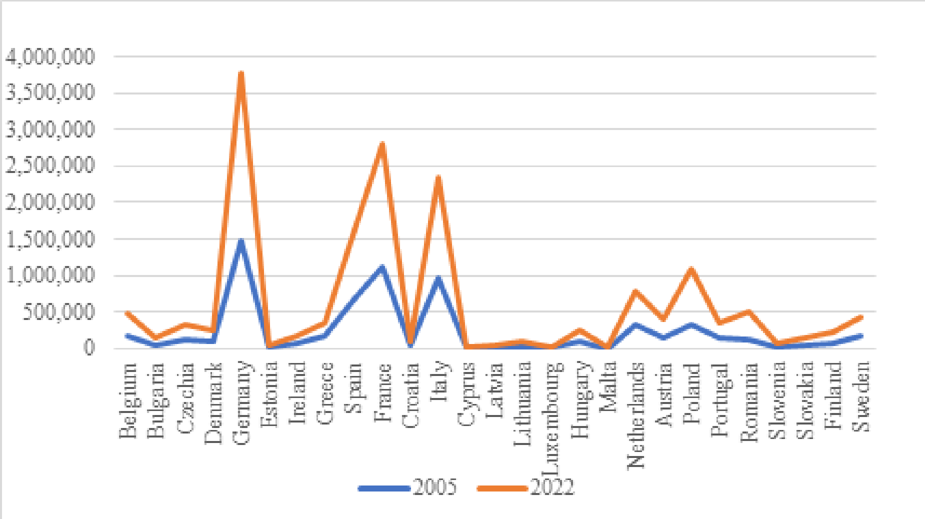

Figure 2. Purchasing power parity, 2010 aggregates [11].

When we compare the countries from 2005 to 2022, *PPP* has grown during the period. However, Bulgaria, Croatia, Cyprus, Estonia, Hungary, Latvia, Lithuania, Malta, Slovakia, and Slovenia had a slight increase. In Czechia, Romania, and Poland, *PPP* showed a meaningful rise. When we investigate descriptive statistics in **Table 1**, we can evaluate the properties of variables.

Table 1. Descriptive statistics.

	PPP	***arrears***
Mean	312,961.41	11.43
Standard Error	65,509.33	1.14
Median	135,201	8.75
Std. Deviation	481,393.32	8.20
Variance	2.3174×10^{11}	67.30
Kurtosis	6.07	5.26
Skewness	2.45	2.03
Maximum	5246	2.7
Minimum	2,302,196	45.5

In **Table 1**, the mean is greater than the median, meaning that both *PPP* and *arrears* are skewed to the right. The standard deviation shows the positive and negative spread among the data. The symmetry of the data distribution, skewness, is in a reasonable range. Kurtosis, the scale of sharpness/flatness, shows that two variables are too peaked because of a greater than 2 value [12].

Economic security differs across most fields, such as the environment and energy, well-being, the business world, health, food, and institutional arrangements. In economic (in)security, we mention the studies done by Bağlıtaş and Atik [13], Carton et al. [14], Cantó et al. [15], Banks and Bowman [16]. Cantó et al. [17], Khadzhynova et al. [18], Gryshova et al. [19], Romaguera-de-la-Cruz [20], Bossert et al. [21], Ignatov [22], Korovchenko and Kraftová [23], D'Ambrosio and Rohde [24], Hacker et al. [25], Osberg and Sharpe [26], Berloffa and Modena [27], Goul Andersen [28], Osberg and Sharpe [4]. These studies have mainly worked with the same concept as us.

Bağlıtaş and Atik [13] focus on the EU's economic security and physical safety. They employ principal components and cluster methods to analyze the relative and changing performance of the old and new member countries for 2008 and 2021. They concluded that other members, such as Luxembourg, Netherlands, Czechia, Germany, and Sweden, had drawn a successful picture, while Greece had the lowest level. Furthermore, the cluster method reveals four clusters. New members belong to heterogeneous clusters, with five in the first, six in the second, and two in the third cluster.

Carton et al. [14] approach the topic of financial well-being and subjective practices in Ireland. Their focus group is 12 households counted, and the method is the survey for October 2020. Subjective behaviors differ from saving patterns to money management. The results suggest the significance of self-discipline characteristics for controlling unseen financial expenses. Cantó et al. [15] accept economic insecurity as a significant part of well-being and investigate measuring economic insecurity in Spain. They studied the indicators of insecurity and decided that indices using subjective and objective variables might be a better alternative.

Khadzhynova et al. [18] detected that Finland, Denmark, and the Netherlands have the highest level while Bulgaria and Romania have the lowest level of economic security in the EU. They took the time to escape during 2010–2019 and various indices connected to economic, social, political, and environmental variables.

Banks and Bowman [16] focused on the economic insecurity aspects under riskscape and timescape contexts for Australia. Risks relevant to unreliable jobs and income uncertainty cause financial lives to be unstable. Risk escapes and time escapes make transitory and economic insecurity noticeable. Cantó et al. [17] studied the EU with a multi-dimensional approach in 2008 and 2016. They use objective and subjective indicators together. They find that being less educated and unemployed are the most effective variables. Moreover, objective indicators also have more influence on well-being in post-transition Eastern European administrations than long-life capitalists.

In the paper of Gryshova et al. [19], they focused on Ukraine and the EU members for the length of three years (2016–2018). They made a composite index for economic security with the help of economic, social, political, and ecological sub-indicators of sustainable development. The findings showed that there was a remarkable enhancement but changeable in orders for five countries (Denmark, Luxembourg, Finland, Sweden, and the Netherlands) in the EU. Ukraine does not make any improvement. They also conducted a clustering analysis for the countries and revealed three clusters: (1) The best; (2) middle; (3) the worst economic security. Eight of the new members are in the third cluster, and five of them are in the second cluster.

Three EU countries—Spain, France, and Sweden—in Romaguera-de-la-Cruz [20] contributed to the different sides of insecurity, such as higher levels of education and changeable job contrasts, as individuals rise. He uses cross-section data for the households in Spain, France, and Sweden from 2008 to 2016. Spain and France show the same pattern related to diminishing, but not Sweden.

Among the political studies, Bossert et al. [21] tried to analyze the relationship between economic insecurity (EIS) and political preferences in the United States, the United Kingdom, and Germany with panel surveys from 1991 to 2008. They found that EIS leads to more political activism and in favor of votes for the rights. Moreover, the steady significant influence of ES depends on per-capita income, homeownership, and employment status in the current and past.

In ten years from 2007 to 2017, Ignatov [22] analyzed economic threats for the EU. He used different parameters to catch the condition of economic security. These parameters are debt, income growth rate, fixed capital accumulation, factor productivity, and technical and institutional improvement. When all parameters are evaluated, the overall value indicated that economic security declined during the period. Thus, the qualitative and quantitative methods revealed the ineffectiveness of the European Union.

In the context of economic and personal safety, Korovchenko and Kraftová [23] studied the period of 2010–2015. They use various indicators for these two dimensions, such as material deprivation rate and depth, youth unemployment rate, assault, and theft. They found that the economic and individual security situation generally did not progress and was volatile during the period.

Osberg and Sharpe [26] revised the economic security index by using datasets of poor and rich countries. They first investigated the index for wealthy countries in the OECD and later compared it with 70 countries that have various income levels. It is concluded that the modified/augmented index should include nutrition production volatility, healthcare costs, and single-parent poverty, and old age poverty [7,20].

Berloffa and Modena [27] worked with income volatility and intergenerational inequality in Italy from 1995 to 2007 for citizens. They use a well-being index consisting of consumption flows, wealth stocks, employment security, and equity. This augmented index reveals that well-being growth rates are much lower than income, and well-being reductions are higher, particularly for the private sector.

Goul Andersen [28] focused on economic security and well-being throughout labor market integration for Danis people between 1994 and 1999. He constructed the economic hardship index with three dimensions. The results reveal that economic hardship is more effective in well-being reduction than unemployment and causes an increase in job seeking. However, this hardship does not have any positive influence on labor market integration.

Unlike the other studies, Osberg and Sharpe [4] tried to construct a better index of well-being. They used different variables for the United States, United Kingdom, Canada, Australia, Norway, and Sweden from 1980 to 1999. They concluded that a better index should consider economic security besides other variables such as income distribution and per capita spending streams. Moreover, there are various indexes in the context of ES, Bossert et al. [21], Mutchler et al. [29], D'Ambrosio and Rohde [24], Hacker et al. [25], Rohde et al. [30], and Bossert and D'Ambrosio [31]. They worked with different and common variables for the indexes.

Our paper's subject is to investigate the effects of the EU on relatively new members for economic security related to well-being concepts. This paper aims to analyze the periodic effect of EU integration on new members in an economic security context. These new members have a relatively low level of development. A union offers various benefits such as socioeconomics, security, stability, and a business environment for the members. Thus, new members might move to a higher level of development. We can detect the changes throughout the related indicators. In this sense, we will analyze the changes in *arrears* and *PPP* using the DID method. This method is barely unique relative to other studies focusing on the connectedness between well-being and economic security. To summarize the literature, we want to depict that there is any significant difference in the EU for relatively new members. We could not find any comparative studies in the literature. For this reason, our study sheds ight from another perspective for economic security with a different analyzing method. Thus, we find out whether the influence of the EU is valid on new members or whether there is a general tendency for the variables beyond the union. The following chapters set forth DID methodology and empirical results.

2. Difference-in-difference methodology

Implemented policies (such as financial and income), programs (such as diets and treatment processes), and crises (such as financial, structural, lockout, and pandemic) faced by countries have impacts on different decision units. Various methods are developed to measure effectiveness or consequences. These methods, called impact assessment, are included and are related to outcomes and impact steps in the monitoring and evaluation processes. In this context, we apply the DID method as an impact evaluation method [32].

DID has two critical assumptions about the units that have time-invariant and unobserved heterogeneity in characteristics. The evaluation process consists of two different groups: Participants and non-participants [32]. Furthermore, time data is also considered as two subgroups for the absence and existence of an action such as treatment, intervention, application, or policy implementation. This kind of discrimination reveals the impact of the actions [33]. Thus, we can compare the differences in pre- and post-action results in terms of focus and control groups [34]. The equation, where Y_i represents the result [35].

$$Y_i = \alpha + \beta T_i + \gamma t_i + \delta(T_i t_i) + \varepsilon_i \quad (1)$$

where α, β, γ, and δ, respectively are constant term, focus group-specific effect (or intervention), time trend, and true effect of an action (intervention × time). Our purpose is to estimate a valid value of δ [35]. Y_i is an outcome when we formulate the logic of DID [36].

$$\mathrm{DID} = \left(\bar{y}_{T,t-a} - \bar{y}_{T,t-b}\right) - \left(\bar{y}_{C,t-a} - \bar{y}_{C,t-b}\right) \tag{2}$$

where the average value of the outcome variable ($\bar{y}$) before and after treatment (T) is represented as $\bar{y}_{T,t-b}$ and $\bar{y}_{T,t-a}$ respectively. The average values of control variables before $\bar{y}_{C,t-b}$ and after $\bar{y}_{C,t-a}$ are in the second part of the Equation (2). These parts compute the difference between participants and non-participants before and after the implementation/program [32].

In this method, there is a significant criterion assuming the parallel trend of outcome and control variables. Parallel trend refers that the tendency lines have different beginning points but are parallel for participants and non-participants before treatment. This assumption clarifies the net effect of treatment on participants [33]. In **Figure 3** we can illustrate all effects.

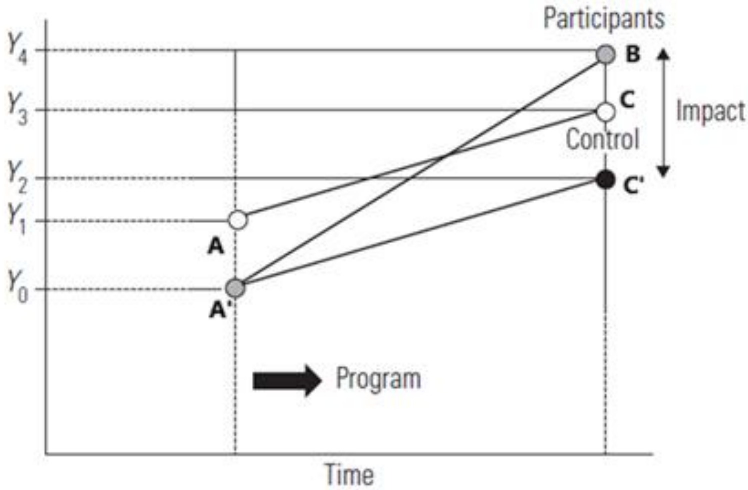

Figure 3. The illustration of treatment effect [32].

Before treatment, we can depict the parallel trend assumption with lines of $\mathrm{AC}//\mathrm{A'C'}$. The change in time for participants is $|\mathrm{BC'}|$ distance, and for non-participants, is $|\mathrm{CC'}|$ distance. DID estimation revealed whether the distance between $|\mathrm{BC'}|$ is statistically significant or not. Otherwise, being or non-being participants in the treatment are indifferent.

The DID method has some limitations/disadvantages, particularly associated with before-after treatment/policy periods. Only two periods give effective results, but multiple periods may lead to confusing findings. The expected positive sign may turn to the negative or vice versa [37]. Another limitation is about the parallel trend assumption. The critical factor is to obtain two groups (control and treatment) that are parallel and absent of intervention. The last limitation is for undetectable variables, which are changeable, not fixed in time. Because this method can catch fixed and undetectable variables [34,38,39].

A robustness check is possible with placebo or additional control groups. In the first situation, we duplicate the analysis with placebo groups that are not included in treatment or not affected by policy intervention. Therefore, if we could not detect any effect of this group, the model robustness becomes more powerful. Another check method is to add one more control group having similar properties to the original control group. We expect that this group indicates the equal treatment effect with the original [40].

3. Data and econometric analysis

3.1. A-data

This variable has binary values for two different domains; one is the time domain before implementation as “0” and after implementation as “1”; the other is the cross-section domain as “1” for new members and “0” for old members in the EU. Thus, we produce a new variable by using time and implementation dummies. This transaction gives information about the EU making a significant contribution to the economic security of relatively new members. We accept the countries that joined the union after 2004 as new members and the others as old members. The logic behind choosing new members rather than old members is mainly related to the economic power of countries. In this line, old members, particularly first members, illustrated gorgeous development for a long time. Although the new members are smaller in accordance with their population, income, financial strength, and other economic indicators.

The toughest struggle is to determine before and after time domains. Due to lack of data, we chose the starting point as 2005, and the end point was determined as 2022, which is the last date we can access the yearly data. The longer the time interval, the more accurate it will be to measure the effect.

Besides that, we use two indicator variables related to economic security. These variables are purchasing power parity (*PPP*) and *arrears. PPP* is actual individual consumption and is based on 2010 measurements. *Arrears* are a measurement for the inability to face unexpected financial expenses, the percentage of income, and are relevant to mortgage or rent, utility bills, or hire purchase retrieved from the Eurostat website belonging to the European Commission (EC). We chose these variables from the report on quality-of-life indicators: Economic security and physical safety statistics published by the EC.

3.2. B-econometric analysis

In **Table 2,** time is a dummy for the time domain, and tcall is another dummy representing the member. The time variable gets “0” for the regime-shifting 2005 year and “1” for the time long after the regime, as 2022. Tcall gets “0” for the old and “1” for the new members. Moreover, DID is a mixed variable for time and call. It takes “1” for the new members and the year 2022; otherwise, “0”. After the regression estimation, we calculate the significance of the period for the new members for *arrears* and *PPP*. Regression results for *arrears* in **Table 2**.

Table 2. Linear regression results for *arrears*.

arrears	**Coef.**	**Std. Err.**	***t***	***P* > |*t*|**	**[95% Conf. Interval]**
time	1.0612	3.196835	0.33	0.741	−5.366491, 7.488844
tcall	6.72	2.814143	2.39	0.021	1.061786, 12.37821
did	−10.8513	3.866286	−2.81	0.007	−18.62487, −3.077487
cons	10.38	2.009217	5.17	0.000	6.340199, 14.4198

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

In the first step of the process, we make an estimation with the DID variable. Later we detect that there is a significant change between the old (control group) and new (treatment group) members. The second step illustrates that the duration of being members for the new countries is beneficial to diminish the quantity of *arrears*. In **Table 3**, the value of DID is statistically significant and negative. It means that the debt of new members decreases throughout the union.

Table 3. Difference-in-differences estimation results for *arrears*.

	Control	**Treated**	**Diff (T-C): t-b**	**Control**	**Treated**	**Diff (T-C): t-a**	**Diff-in-Diff**
Coef.	10.38	17.1	6.72** (−3.187)	11.441	7.31	−4.131 (−3.111)	−10.851** (−4.453)

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$, Standard errors are in parenthesis.

After *arrears*, we want to focus on *PPP*. While the *arrears* variable is a kind of negative event in life, *PPP* positively affects life during rising. For this reason, the expected coefficient is positive and statistically meaningful. The procedure is to estimate the general regression model and later detect significant differences between the periods for the new members. Linear regression and DID estimations are in **Tables 4** and **5**.

Table 4. Linear regression results for *PPP*.

PPP	**Coef.**	**Std. Err.**	***t***	***P* > |*t*|**	**[95% Conf. Interval]**
time	186,191.9	193,743.8	0.96	0.341	−202,954, 575,337.8
tcall	−274,891.1	110,829.2	−2.48	0.017	−497,498.1, −52,284.19
did	−113,442.9	208,037.6	−0.55	0.588	−531,298.7, 304,412.9
cons	342,684.9	106,776.6	3.21	0.002	128,217.8, 557,152

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Table 5. Difference-in-differences estimation results for *PPP*.

	Control	**Treated**	**Diff (T-C): t-b**	**Control**	**Treated**	**Diff (T-C): t-a**	**Diff-in-Diff**
Coef.	3.40×10^5	6.80×10^4	-2.7×10^5 (1.8×10^5)	5.30×10^5	1.40×10^5	-3.9×10^5** (1.8×10^5)	-1.1×10^5 (2.6×10^5)

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$, Standard errors are in parenthesis.

Table 5 demonstrates that the DID coefficient δ is not statistically significant. Meaning that the EU does not make any difference in purchasing power parity of the relatively new members. The reason for this result is probably the natural rising trend of welfare of individuals. These new member countries could show a rising rate of *PPP* in time beyond the union.

4. Discussion and conclusion

Quality of life indicators have been the most popular subject in recent years. Eurostat [1] determines these indicators based on these categories: Material resources, leisure time, social connections, economic security and physical safety, governance and fundamental human rights, environmental conditions, and life experience. In this study, we evaluated economic security apart from physical safety. Economic security is a tool that rates the ability to cope with unforeseen financial struggles using material resources and the perception of the struggles.

Moreover, the European Union listed the benefits for the members as a peaceful environment, political stability, mobility of individuals, single market facilities, support for development, cultural diversity, safety, and other advantages [41]. However, there are general benefits for the members, and the capability of getting benefits differs. This capability depends on many factors, such as how big the country's economy was when it became a member. Besides that, a country facing a financial struggle or crisis might experience a more severe form because of being in a union. On the other hand, our study also investigated the changes in *arrears* and *PPP* variables. The analysis illustrates the contradictory role of EU policies and integration in shaping economic indicators and, consequently, the economic security and quality of life of its members. While the *arrears* decreased significantly, the *PPP* variable did not show a significant increase despite the integration from 2005 to 2022.

When we look at detail in DID findings, arrears reduced from 2005 to 2022 with 17.100 and 7.310. This reduction is not sourced from time-variant factors but also the union. Besides this, the EU does not have a significant effect on *PPP*. However, this variable increased from the period with 2.1×10^4 and 4.1×10^4, respectively; this increase is not related to the EU. We can interpret this result as coming from the natural upward movement of *PPP*.

In literature, there are two kinds of study. One of them is related to the connection between well-being and economic security and the determinants of ES. The other tries to measure progress and the state of economic security. If we compare our findings with the second piece of literature, the general outlook of new members does not depict a successful process in accordance with economic security. Bağlıtaş and Atik [13] made a clustering analysis and revealed heterogeneous grouping for economic security and physical safety. The second and fourth clusters consist of only new members; the first and third clusters include old and new members.

A similar study made by Gryshova et al. [19] illustrated a worse finding for economic security. They employed a composite index for all components of sustainable development. There are three clusters for the EU members. Moreover, they discovered that more than half of the members have had the worst economic security for three years. Ignatov [22] analyzed the EU during an eleven-year time frame (2007–2017) with various indicators. The result of the analysis depicted diminishing value of economic security. Korovchenko and Kraftová [23] evaluated ES and physical security (PS) together with different variables. ES and PS are not enhanced and fragile from 2010 to 2015. Khadzhynova et al. [18] found the lowest value of economic security for Bulgaria and Romania and the highest value for Finland, Denmark, and the Netherlands. This finding is supportive evidence for our study.

To sum up, we infer from the findings of associated studies that the impact of the EU on the economic security of new members is not so glorious for different periods. Although some indicators might make a considerable improvement. The European Union may not be so effective in spilling over to new and less wealthy countries.

In economic security, further studies can analyze the impact of unions using different variables and indexes. Moreover, microdata comparing different periods could give more precise results for evaluation. Other econometric/statistical techniques measuring structural breaks or regime shifts could be alternative methods. Furthermore, if possible, adding a placebo or more control groups could make the analysis more robust. This analysis is particularly possible with questionnaire data and multiple periods with the same treatment and control groups.

Author contributions: Manuscript design, HHB; writing, HHB; data, HHB; analysis, HHB; supervision, HA; critical review, HA. All authors have read and agreed to the published version of the manuscript.

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Article

Energy resources: Their causal relationship with ecology and environments

Romanus Peter Lyanda[1,*], Fredrick Ojija[2]

[1] Department of Electrical and Power Engineering, College of Engineering and Technology, Mbeya University of Science and Technology, Mbeya 131, Tanzania
[2] Department of Earth Sciences, College of Science and Technical Education, Mbeya University of Science and Technology, Mbeya 131, Tanzania
*** Corresponding author:** Romanus Peter Lyanda, romanuslyanda2@gmail.com

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Abstract: Energy resources are critical drivers of economic development and societal progress, but their extraction, conversion, and use have profoundly impacted ecological systems and the environment. Therefore, it is essential to explore the relationships between energy resources and the environment throughout history. This paper examines the causal relationships between energy resource utilization and environmental changes, addressing both renewable and non-renewable energy sources. We analyze the environmental consequences of energy extraction and consumption, including pollution, habitat destruction, and climate change, and evaluate sustainable approaches to mitigate these effects. Fossil fuels have been the primary source of energy and are major contributors to greenhouse gas emissions, air and water pollution, and habitat destruction, all of which exacerbate global climate change. On the other hand, renewable energy sources such as wind, solar, and hydroelectric power are considered more sustainable. However, they also have environmental impacts, such as habitat disruption and high resource consumption. Researchers argue that trade-offs must be managed between increasing energy use, facilitated by technological advancements, and achieving sustainability. Energy generation and ecological goals should not be viewed as opposing or irreconcilable. With the implementation of appropriate policies, measures, and guidelines, energy production can be aligned with efforts to mitigate climate change and promote sustainability.

Keywords: energy resources; environmental impact; climate change; sustainability; renewable energy

1. Introduction

Energy is a key element in achieving economic growth and development in any society. However, energy resources are more than just enablers of development, as their collection, transformation, and use significantly impact ecological systems and the environment at large. Therefore, it can be said that energy resources and their use have the potential to cause environmental consequences. Since the Industrial Revolution, fossil fuels—including coal, oil, and natural gas—have been the dominant sources of energy and key drivers of industrialization and urbanization. Nonetheless, their extraction and use emit large amounts of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), which contribute to global warming and climate change [1]. The detrimental use of fossil fuels contributes to air, water, and land pollution, as well as habitat destruction and species extinction [2]. More effective and environmentally friendly alternatives to fossil fuels include solar, wind, and hydroelectric energy sources. The use of renewable energy provides benefits such as reduced greenhouse gas emissions and the preservation of biodiversity. However, it is important to note that renewable energy technologies also have their own environmental impacts. For example, the construction of wind turbine farms can negatively affect bird and bat populations [3] or hydroelectric dams, while providing renewable energy can adversely affect aquatic ecosystems [4].

Nuclear energy generates power with minimal greenhouse gas emissions, making it a low-carbon alternative to fossil fuels. However, it poses significant challenges, including the management of radioactive waste and the risk of catastrophic accidents, as demonstrated by events like Chernobyl and Fukushima [5]. The long-term management of radioactive waste and the high expense of nuclear safety measures continue to be serious concerns [6]. Global energy demand is projected to increase by over 50% in the next 20 years [7], making it imperative to consider the environmental implications. Sustainable energy practices must be developed to meet energy needs without compromising the environment.

This review paper aims to analyze the environmental impacts of energy resource utilization, considering both renewable and non-renewable energy sources. It examines energy use and its ecological effects to identify strategies that can mitigate negative impacts and promote ecological sustainability.

2. Literature review

Search platforms such as Google Scholar, Web of Science, and ScienceDirect were utilized for the literature review. Many relevant papers identified during the search were cited in this study due to their importance to the topic. The close relationship between energy resources and the environment has been a central focus of numerous research studies over the past few decades. With the increasing global demand for energy, it is essential to understand the environmental implications of various energy resources to develop sustainable and long-term solutions. This review explores the ways in which energy resource consumption contributes to environmental changes, with a particular focus on both renewable and non-renewable sources. It discusses the environmental impacts of energy consumption and patterns of energy use, aiming to identify strategies that minimize negative effects and promote environmental sustainability.

2.1. Non-renewable energy resources and environmental impacts

2.1.1. Fossil fuels and environmental impact

For centuries, humanity has depended on fossil energy sources such as coal, oil, and gas for primary energy production and industrial growth, owing to their abundance and affordability. However, the excessive use of fossil fuels has caused significant damage to ecosystems. Their combustion releases large quantities of greenhouse gases, including CO_2 and CH_4, which contribute to global warming and climate change worldwide [1]. The long-term effects of climate change pose severe threats to biodiversity, food security, and human health [8]. Another major drawback of relying on fossil fuels is air pollution and its associated health impacts. Emissions such as particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) are significant contributors to air pollution [9]. These pollutants are harmful to human health, causing respiratory and cardiovascular diseases [10] as seen in **Figure 1**. According to the Global Burden of Disease study, air pollution from fossil fuels accounts for millions of premature deaths annually [11]. Furthermore, large-scale extraction of fossil fuels destroys habitats and reduces biodiversity, as vast areas of land are excavated for oil and gas drilling and mining operations [12].

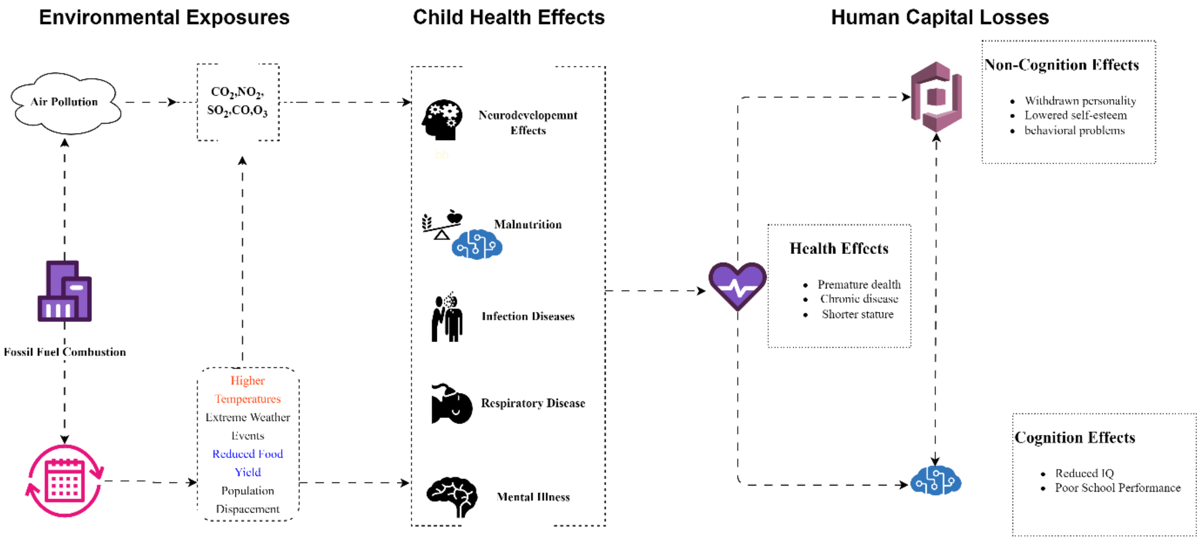

Figure 1. Routes from burning fossil fuels to potential effects on children's health and related losses in human capital [13].

Some studies have documented that water resources are increasingly under threat due to pollution caused by oil spills, coal mine drainage, and hydraulic fracturing fluids (fracking), all of which are harmful to both humans and the environment as shown in **Table 1**. Aquatic ecosystems are particularly vulnerable to these threats [14]. Additionally, the extraction of fossil fuels often results in significant land degradation and biodiversity loss. Coal mining, especially through mountaintop removal, can permanently alter landscapes and ecosystems [15]. Similarly, oil and gas drilling disrupts natural environments, leading to habitat fragmentation and species loss [16].

For example, air pollution from fossil fuels accounts for millions of premature deaths annually, with an estimated 8.7 million deaths globally linked to fossil fuel-related air pollution (PM2.5) in 2018 [17]. Additionally, 74% of the greenhouse gas (GHG) emissions in the United States in 2019 came from fossil fuels [18]. With global CO_2 emissions reaching 36.8 billion metric tons in 2022, the primary cause of human-induced climate change continues to be the burning of coal, oil, and natural gas for energy production [19].

The usage of fossil fuels has a significant financial cost in addition to its negative effects on the environment. Fossil fuel-related air pollution is predicted to cost the world $2.9 trillion a year, or 3.3% of Gross Domestic Product (GDP), in lost productivity and medical costs [20].

Comparisons of energy efficiency also draw attention to the drawbacks of fossil fuels. For example, combined-cycle natural gas plants can achieve efficiencies of over 60%, but coal-fired power plants only operate at 33%–40% efficiency [21]. However, in terms of sustainability and efficiency, renewable energy sources like solar and wind perform better than fossil fuels. While solar photovoltaic (PV) efficiency has increased to about 20%–25%, modern wind turbines have a capacity factor of 35%–50%, with offshore installations reaching even greater levels [22,23].

There are major financial advantages to switching to renewable energy as well. In 2021, the renewable energy industry employed 12.7 million people globally, and forecasts suggest that number will continue to rise as clean energy investments increase [24,25]. Additionally, the levelized cost of electricity (LCOE) for solar PV has decreased by 89% and for onshore wind by 70% since 2010, indicating a significant drop in the cost of renewable energy over the last ten years [26,27]. In comparison, the worldwide cost of fossil fuel subsidies, including explicit subsidies, health care expenses, and environmental harm, was $7 trillion in 2022 [28].

Table 1. Environmental and ecological impact of fossil fuels.

Impact Type	Description	Data/ Statistic	References
Greenhouse Gases	CO_2 and CH_4 emissions contribute to global warming and climate change.	Fossil fuels accounted for 74% of U.S. GHG emissions in 2019	[29]
Air Pollution	Release of SO_2, NOx, PM, and other pollutants.	Air pollution from fossil fuels is linked to millions of premature deaths annually	[30]
Water Pollution	Contamination from oil spills and fracking fluids	Fracking wells use 1.5–16 million gallons of water, potentially contaminating groundwater	[14]
Land Degradation	Habitat destruction and soil erosion from mining and drilling activities	Coal mining leads to acid mine drainage, impacting aquatic ecosystems	[15]
Ocean Acidification	CO_2 absorption by oceans changes their chemistry, harming marine life.	Ocean acidity has increased by 30% over the last 150 years	[31]
Ecosystem disruption and Biodiversity Loss	Habitat destruction leads to loss of species and ecosystems	Significant biodiversity loss due to habitat fragmentation and pollution	[32]
Resource Depletion	Finite nature of fossil fuels necessitates sustainable alternatives.	Fossil fuels are non-renewable and contribute to resource depletion	[33]

2.1.2. Nuclear energy and environmental risks

Nuclear energy is one of the few resources that does not emit carbon dioxide when used to produce electricity, making it an alternative to fossil fuels. However, nuclear energy also has its disadvantages, particularly concerning environmental and safety issues. One of the major challenges is the disposal of radioactive waste, which remains hazardous for thousands of years to ecosystems and human health [34]. The United States alone produces over 2000 metric tons of nuclear waste annually, and as of 2020, more than 80,000 metric tons of spent nuclear fuel had accumulated in temporary storage at sites like the Yucca Mountain repository [35]. The disposal of this waste has been a contentious issue, with limited progress in developing permanent repositories.

The risk of severe accidents, such as the Chernobyl disaster in 1986 and the Fukushima Daiichi plant incident in 2011, highlights the dangers of nuclear power [36]. These accidents resulted in significant ecological and human consequences, including radioactivity and the contamination of surface and groundwater sources [37]. Moreover, the high costs of constructing and operating nuclear power plants, coupled with stringent safety regulations, present economic challenges [38]. Public concern about the safety and environmental impacts of nuclear power has led to resistance against new nuclear plants in many countries. A survey conducted by the Pew Research Center in 2019 found that only 49% of Americans supported the use of nuclear energy, compared to 78% support for solar power and 71% for wind power [39].The long-term management of nuclear energy requires robust safety protocols, efficient waste management systems, and public acceptance.

2.2. Renewable energy and environmental challenges

Renewable energy sources, such as solar, wind, and hydroelectric power, have emerged as potential substitutes for fossil fuels. These sources generate energy without emitting greenhouse gases during operation, thereby reducing the overall carbon footprint [40,41]. However, renewable energy technologies also present environmental challenges. Only publications discussing the trade-offs or effects of renewable energy types on the environment and nature conservation were considered relevant.

Changes in land use and resource extraction for renewable energy development can disturb the environment and are usually not sustainable. For instance, wind energy farms have been linked to increased bird and bat deaths due to strikes with turbine blades [42]. Likewise, extensive solar farms can change the cover of the land and subsequently affect the local ecosystems by fragmenting habitats [43]. Even though hydropower energy is more constant and reliable, it comes at the cost of altered water flows, which via loss of biodiversity and the Riverine species, habitat damage, and river degradation [44]. Increased energy production from renewable sources forces and transforms their sources from forests, wetlands, and crop areas, resulting in a reduced capability of renewable energy sources to sustain ecosystems. Also, the studies have addressed that the construction of renewables will produce a lot of biodiversity loss, and this has greatly concerned conservationists.

The types of impacts examined include air, soil, and water pollution, greenhouse gas emissions, hydrological changes, landslides, soil erosion, deforestation, habitat fragmentation, and biodiversity loss, as listed in **Table 2**. The most common renewable energy sources in Tanzania—solar, wind, bioenergy, hydro, and geothermal—are the primary focus of this article.

Table 2. Summary of effects of nature protection and the environment from renewable energy sources [40].

Type	Air Pollution	GHG Releases	Water Contamination	Land Slide	Soil Pollution	Deforestation	Biodiversity and Habitat loss
Solar	X	X	X	X	X	?	?
Wind	?	X	X	X	X	X	?
Hydro	√	√	√	√	√	√	√
Bioenergy	√	√	√	X	√	√	√
Geothermal	√	X	√	√	√	√	√

√: Existing data and theoretical connections.
?: There is a theoretical connection but no supporting data in this field of study.
X: no proof was discovered.

Solar power is considered a low-emission energy source, but its long-term environmental impact is significant. According to studies, the production of photovoltaic (PV) panels creates hazardous waste, including silicon tetrachloride as a byproduct that leads to land and water pollution [45,46]. Large-scale solar arrays also sometimes need significant changes in land use, which fragments habitat. In Arid regions, the installation of solar farms has been shown to reduce natural plant cover by 25% [47,48]. Furthermore, because of its material-intensive components, high-temperature plumbing (HTP) in concentrated solar power (CSP) facilities may result in higher emissions [49]. In countries like India and China, where solar power expansion is accelerating, there are growing concerns about waste management and land degradation [50]. India's ambitious solar farm projects in Rajasthan have been criticized for disrupting fragile desert ecosystems [51,52]. Similarly, in China, the rapid deployment of PV plants has led to increased concerns about silicon mining and water usage, particularly in arid regions [48,53].

Wind power is one of the most ecologically harmless renewable energy technologies in terms of carbon footprint, producing just 11 g CO_2-equivalent per kWh as opposed to coal's 820 g CO_2-equivalent per kWh [54,55]. However, wind turbines have been linked to biodiversity concerns, particularly bird and bat mortality. A study in the United States found that up to 500,000 bird fatalities per year can be attributed to wind farms [56]. Furthermore, building wind turbines changes the morphology of the ground and causes soil erosion, particularly in areas with unstable soil [43]. Changes in the behavior of nearby wildlife populations have also been linked to wind farm noise pollution and electromagnetic disruptions [57]. Concerns over offshore wind farms' effects on marine ecosystems have been raised throughout Europe, especially in Germany and Spain. Studies indicate that fish movement patterns and bottom ecosystems are impacted by turbine foundations [58]. By including artificial reef structures to offset habitat loss, the UK, on the other hand, has been at the forefront of sustainable wind farm design [59–61].

Hydropower projects, despite providing a consistent electricity supply, are coupled with considerable ecological impacts. It has been demonstrated that in some river ecosystems, changes to upstream and downstream water flows can reduce fish populations by as much as 60% [62,63]. For instance, the construction of the Belo Monte dam in Brazil has been correlated with much lower fish diversity and abundance [64]. Large-scale dam projects also contribute to deforestation, with the Amazon region losing over 1 million hectares of forest owing to hydropower expansion [65]. Furthermore, methane emissions from reservoirs might counteract the climate benefits of hydropower; in certain tropical reservoirs, methane emissions can reach 1000 mg/m^2/day [66]. Countries such as Brazil and China have significantly invested in large-scale hydropower. More than 1.3 million people have been displaced by China's Three Gorges Dam, the world's largest hydropower project, which has also caused extensive geological instability [67,68]. Scandinavian nations like Sweden and Norway, on the other hand, have created small-scale run-of-river hydropower plants that preserve energy production while minimizing environmental disruptions [69,70].

Bioenergy is frequently marketed as a sustainable alternative to fossil fuels, although its environmental impact varies depending on the feedstock and land use. The conversion of forests to bioenergy crops has caused a 20% decline in biodiversity in some locations [71]. Furthermore, biomass energy production releases pollutants such as nitrogen oxides and particulate matter, contributing to air quality degradation

[72]. Life-cycle assessment research indicated that bioenergy combustion can produce up to 70 g of CO_2-equivalent per kWh, making its carbon savings largely dependent on sustainable feedstock supply [73]. In the United States, the rise of corn-based ethanol production has caused increasing nitrogen runoff into aquatic bodies, contributing to dead zones in the Gulf of Mexico [74]. Similarly, in Southeast Asia, palm oil biofuel plants have been directly related to deforestation, causing serious habitat loss for endangered species such as orangutans in Indonesia and Malaysia [75].

It is important to note that while certain renewable energy technologies may have negative impacts on biodiversity, others may have positive effects, as shown in **Table 3**.

Table 3. Biodiversity benefits of different renewable energy pathways.

Renewable pathway	Biodiversity benefit	References
Solar energy	Solar energy plants can provide habitat and feeding grounds, such as grazing, for specific animals. This includes photovoltaic panels installed on roofs and building facades	[76]
Wind Energy	Wind power projects may benefit terrestrial wildlife by reducing traffic, increasing food availability, and reducing predators	[77]
Hydropower	Hydroelectric projects can provide new homes for some iconic species	[78]
Bioenergy	Bioenergy landscapes, such as miscanthus and switchgrass, may offer ecosystem services such as habitat and food, in contrast to intensive monoculture farming approaches	[79–82]

2.3. End-of-life of renewable energy systems

Driven by the worldwide movement toward greener energy sources, the fast expansion of renewable energy infrastructure presents the management of the end-of-life (EOL) disposal and recycling of components like wind turbines, solar panels, and energy storage batteries as a difficulty. While these technologies offer lower carbon emissions and a cleaner environment, disposal presents distinct issues. These issues are exacerbated by the difficulty of recycling important minerals like lithium, rare earth elements (REEs), and cadmium, which are essential to these systems. Addressing these concerns is critical to ensure that renewable energy sources are actually sustainable, without causing additional environmental problems as they age.

Wind turbines are crucial for renewable energy production, but their disposal and recycling pose significant challenges. The blades, made from lightweight, durable materials like fiberglass or carbon fiber, pose a significant challenge. The International Renewable Energy Agency (IRENA) predicts a global waste of up to 50 million tons of blades by 2050 [83]. Despite efforts, the scale of wind turbine waste continues to grow. The average lifespan of a wind turbine is 20 to 25 years, after which blades need to be replaced. As wind energy expands globally, efficient, cost-effective, and environmentally friendly recycling solutions are needed.

Solar panels, composed of silicon, glass, aluminum, and sometimes cadmium and lead, have a lifespan of 25–30 years [84]. The recycling process is complex and costly due to the presence of hazardous materials [85]. Less than 10% of solar panels are recycled globally, attributed to difficulties in material separation, lack of proper recycling infrastructure, and low economic incentives. The growing solar energy market leads to a potential waste crisis in the future. The recycling process involves disassembly, material separation, and recovery of valuable components. Recovery of rare materials like cadmium and indium is challenging, necessitating advanced techniques like hydrometallurgical processes.

Rising global demand for energy storage solutions, especially lithium-ion batteries (LIBs), is causing a growing challenge in battery disposal and recycling. Lithium, cobalt, and nickel are critical minerals in LIBs, but their extraction can have significant environmental and social impacts [86]. Currently, only 5% of batteries are recycled, involving costly and energy-intensive processes. The shortage of recycled lithium and other critical minerals has led to concerns about "mining" electronic waste, e-waste, to recover valuable metals. With the growing demand for renewable energy systems, recycling these critical materials becomes even more urgent.

2.4. Case studies illustrating the impacts of renewable and non-renewable energy on ecology and environment

Coal mining and other non-renewable energy sources have been linked to widespread habitat loss and pollution, which ultimately results in the extinction of species, according to some case studies. For example, the loss of habitats vital to species such as the eastern hellbender salamander (Cryptobranchus alleganiensis) due to mountaintop removal mining in Appalachia, USA, has contributed to the fall in biodiversity [87]. In a similar fashion, the Colombian Cerrejón coal mine has drastically reduced habitat, putting species like the jaguar in jeopardy [88,89] and negatively affecting indigenous populations. Due to habitat loss, species like the black-throated finch (Poephila cincta) and bilby (Macrotis lagotis) are under danger from the Adani Carmichael coal mine in Australia [90]. In Bulgaria, coal mining along the Black Sea coast has also destroyed coastal ecosystems and eroded soil, which has an impact on migratory bird species [91]. In the Kuzbass region of Russia, coal mining has contaminated the air and water, harming aquatic life and local ecosystems [92].

However, renewable energy initiatives like solar and wind may also have an impact on biodiversity, but frequently in different ways. Collisions with turbines in wind farms, like those in the UK, have killed birds and bats [93]. In the North Sea, offshore wind farms have an effect on marine ecosystems, despite the fact that certain species benefit from the constructions [94]. There are worries regarding habitat destruction when solar power plants are implemented in environmentally delicate regions, such as the Amazon rainforest [95]. In order to reduce the effects of both energy forms on biodiversity, these case studies emphasize the necessity of meticulous planning and mitigation techniques. Additionally, research shows that in 2012, wind turbines killed over 600,000 bats in the United States, with the Appalachian Mountains seeing the highest fatality rate [96]. According to estimates, wind turbines cause the loss of less than 0.4 birds every gigawatt-hour (GWh) of energy produced, while fossil fuel power plants cause the loss of more than 5 birds per GWh [97].

3. Technological advancements and sustainable energy practices

To link energy generation with environmental preservation, technical advances and regulatory adjustments are necessary. Smart grids, for example, can enhance energy efficiency and reduce environmental impacts. Green product and service innovation includes the development of new items, such as energy-efficient appliances and building designs [98]. Integrating energy storage solutions, such as batteries and pumped hydro storage systems, can improve the reliability of renewable energy sources by addressing intermittency issues [99]. Storage also allows excess energy produced during high production periods to be stored and used when production is low but demand is high. Research and development in the battery field, particularly in lithium-ion and solid-state batteries, have improved their energy density, efficiency, and lifespan, making their commercial use more feasible [100]. Research into carbon capture and storage (CCS) technologies can prevent greenhouse gas emissions from fossil fuel power plants. CCS involves capturing carbon dioxide emissions from fossil fuels and transportation and storing the gas in geological formations. Over time, the economic aspects of this technology have been refined, and the cost of CCS has decreased significantly, making it a more feasible method for reducing carbon emissions [101]. For example, the Petra Nova project in Texas, USA, has been operational since 2017 and is among the largest CCS projects, successfully reducing CO2 emissions from a coal-fired power plant [102].

In terms of policies related to renewable energy sources, the deployment of measures such as carbon pricing, incentives for renewable energies, and emission reduction targets has been identified as crucial in accelerating the transition to sustainable energy systems [103]. Governments and international organizations need to collaborate to design and implement policies that favor the adoption of clean energy sources. For instance, the Green Deal outlines specific objectives, such as reducing greenhouse gas emissions by 2030 and addressing the low share of renewables in the energy supply [104]. Additionally, decentralized energy systems and smarter grids play a significant role in transforming energy generation, transmission, and consumption. Smart grids and decentralized energy systems detect areas with high energy demand and send more electricity to those grids. Local generation within microgrid systems, as well as distributed generation units, reduces reliance on larger-scale power plants and enhances resiliency [105,106].

To meet the world's energy needs economically, continuous innovation and improvement of renewable energy technologies are essential. For example, the development of perovskite solar cells could increase solar energy conversion efficiency at a lower cost than current silicon cells [107]. Furthermore, increased competition in the wind energy market is driven by advancements in wind turbine technology and materials, which have improved energy capture and structural integrity [108]. Technological advances, strategies, and innovative plans are supported by countries through international collaborative initiatives. Setting low-carbon energy policy targets, such as those outlined in the Paris Agreement, represents a global effort to combat climate change [109]. By sharing accumulated knowledge, technologies, and best practices, countries can overcome technical and financial challenges in integrating clean energy solutions. **Figure 2** below shows the advancements and innovations in energy technologies that have significantly influenced resource efficiency and ecological balance.

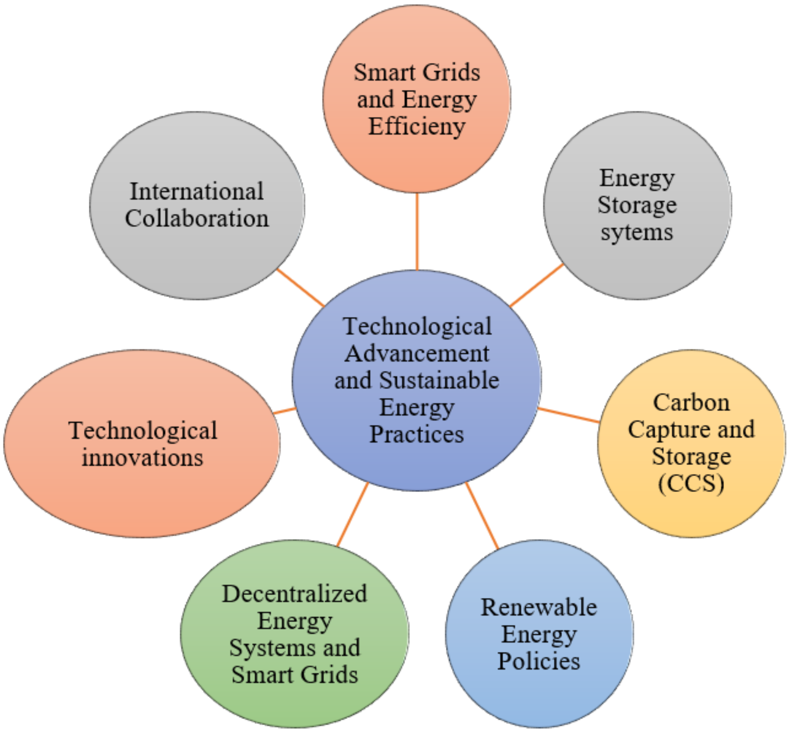

Figure 2. Advancements and innovations in energy technologies.

4. Conclusion

The relationship between energy resources and the environment is complex, with both renewable and non-renewable sources having significant ecological consequences. While fossil fuels have long been the dominant energy source, their extraction and combustion contribute to climate change, air and water pollution, and biodiversity loss. The depletion of non-renewable resources also presents economic and sustainability challenges, necessitating a transition toward cleaner energy alternatives. Renewable energy sources, including solar, wind, hydro, and bioenergy, offer solutions to reduce greenhouse gas emissions and mitigate climate change. However, they are not without drawbacks. Wind farms impact bird and bat populations, large-scale solar farms lead to habitat fragmentation, and hydropower projects disrupt aquatic ecosystems. Therefore, an integrated approach is essential to balance energy production with ecological preservation. Technological advancements, such as smart grids, energy storage solutions, and carbon capture, are critical in improving energy efficiency and reducing negative environmental impacts. Policy measures, including carbon pricing and incentives for renewable energy adoption, can accelerate the transition to sustainable energy systems. International collaboration and investment in research and development will further enhance the viability of clean energy solutions. To achieve a sustainable future, a holistic approach is required, integrating renewable and low-carbon technologies while mitigating their environmental risks. By prioritizing careful planning, impact assessments, and technological innovations, energy production can align with ecological conservation. This balance is vital to ensuring economic development while preserving biodiversity and mitigating climate change.

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Article

Gender role in agroforestry adoption and management in Garo ethnic community of Bangladesh

Sumaiya Binte Rahman Asha[1], S. M. Kamran Ashraf[1,*], Md Tanbheer Rana[2], Saleha Khatun Ripta[3], Mst. Sohela Afroz[1], S. M. Sanjida Tasnim Urmi[1], Al Rahat[1], Shoumika Binte Shafiqe[1], Kazi Kamrul Islam[1]

[1] Department of Agroforestry, Bangladesh Agricultural University, Mymensingh 2200, Bangladesh
[2] Tropical and International Forestry, George August University, Goettingen 37075, Germany
[3] Department of Soil Science, Bangladesh Agricultural University, Mymensingh 2200, Bangladesh
*** Corresponding author:** S. M. Kamran Ashraf, smkamranashraf17@gmail.com

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Abstract: Agroforestry holds significant promise for offering substantial benefits to the Garo ethnic community, who are recognized as one of the primary indigenous groups in the Madhupur region with distinct cultural identities. Given the integral role of community involvement in agroforestry management, particularly in relation to gender dynamics, this study sought to analyze the gender role of Garo men and women in adopting and managing agroforestry practices. Data were gathered from 70 Garo tribal farmers (37 male and 33 female) across six villages practicing various agroforestry techniques in the Madhupur Sal forest area. Using a mixed-methods approach that incorporated semi-structured questionnaires, focus group discussions, key informant interviews, and direct observations, the study identified prevalent agroforestry practices featuring various tree-crop combinations. These included Akashmoni (*Acacia auriculiformis*) paired with Pineapple (*Ananas comosus*) and Ginger (*Zingiber officinale*), as well as other combinations such as Akashmoni-Pineapple-Turmeric, Akashmoni-Pineapple-Papaya, and Akashmoni-Pineapple-Aroid. Both men and women exhibited a moderate to high level of involvement in agroforestry programs, with decision-making processes shared between genders. However, challenges were encountered, particularly by women from ethnic minority backgrounds, including limited technical knowledge, financial resources, and labor availability. Despite these obstacles, both Garo men and women expressed a keen interest in agroforestry practices as a means to enhance their income and livelihoods, forming gender-based partnerships to address associated challenges in a changing socioeconomic landscape.

Keywords: sex-based dynamics; woodland governance; indigenous livelihoods; female empowerment; eco-friendly practices

1. Introduction

Agroforestry stands out as a sustainable land management practice, offering socioeconomic benefits crucial for farmers in Bangladesh. Traditional agroforestry methods contribute to increased species diversity, assured financial returns, and sustained livelihoods [1,2]. With 65% of Bangladesh's population residing in rural areas heavily reliant on agriculture, the pressure on cultivable land is intensifying due to urbanization and industrialization [3]. Agroforestry emerges as a solution to compensate for land losses, offering a blend of agriculture and forestry benefits.

The essence of agroforestry lies in the symbiotic relationship between trees and agriculture, encompassing various practices from trees on farms to farming in forest margins [4]. This integrated approach not only optimizes land use but also promotes biodiversity and ecosystem resilience. Its sustainability stems from trees' multifaceted contributions, including soil stabilization, water retention, and carbon sequestration, which mitigate the impacts of climate change [5]. Particularly for smallholder farmers, agroforestry enhances food security, income, and health while providing economic, socioeconomic, and environmental advantages [6]. The diversified income streams from agroforestry products buffer farmers against market fluctuations and external shocks, thereby increasing their resilience to socio-economic challenges.

In Bangladesh, where meeting the needs of a growing population with limited resources is paramount, agroforestry offers a viable option, surpassing conventional cropping methods [7]. Notably, the involvement of women in agroforestry management is significant, underlining its potential to empower rural communities economically and socially [8]. However, successful adoption hinges on understanding farmers' context-specific knowledge, interests, and challenges.

Gender dynamics play a crucial role in agroforestry adoption and management, reflecting social and biological differences between men and women [9]. In Bangladesh, the Garo ethnic community, known for its matrilineal social structure, stands out for their unique reliance on agroforestry for sustenance [10]. With their significant contributions to Bangladesh's socioeconomic development, understanding how Garo men and women adopt and manage agroforestry becomes imperative.

Garo stands as a significant indigenous group within Bangladesh, characterized by unique ethnic traits. The traditional fabric of Garo society undergoes shifts owing to various socio-economic factors, consequently altering its social makeup and interactions. Foremost among the current hurdles confronting the Garo community is the issue of land rights. Residing in and near the central deciduous Sal (*Shorea robusta*) forests, designated as State forests, they find themselves classified as illegal occupants under the law. The prevailing Vested Enemy Property Act fails to acknowledge their rightful claims to land or land ownership [11].

In this research we tried to explore Garo farmers' attitudes towards agroforestry adoption and management. We also examine the approaches used by Garo men and women in managing agroforestry and seek to identify the major challenges they encounter in agroforestry practices. This research not only sheds light on the role of agroforestry in sustainable land management but also contributes to understanding the intricate dynamics of gender and ethnicity in agricultural practices. Through a comprehensive examination of Garo agroforestry practices, valuable insights can be gained to inform policies and interventions aimed at promoting sustainable agriculture and empowering rural populations.

2. Materials and methods

2.1. Study area

The Madhupur Tract, covering an area of 45,565.2 acres, is commonly referred to as the Madhupur Sal Forest or Madhupur Garh and is situated between 23°50′ to 24°50′ North latitude and 89°54′ to 90°50′ East longitude. Locally known as "chalas," these low hills, rising 3.0–4.5 m above the surrounding fields, are characterized by plains and numerous depressions or "baid," which define the region's topography. The soil in this area consists of highly oxidized reddish-brown clay with a mildly to strongly acidic reaction, along with low organic matter and fertility levels [12]. The region experiences an annual temperature variation between 10 ℃ and 34 ℃, with yearly rainfall ranging from 203 to 229 cm. Additionally, as reported by Hasan et al. [13], the relative humidity fluctuates between 60% and 80%. Our research was conducted in six villages: Dokhola, Auronkhola, National Park, Gaira, Beribaid, and Makundinagar (**Figure 1**).

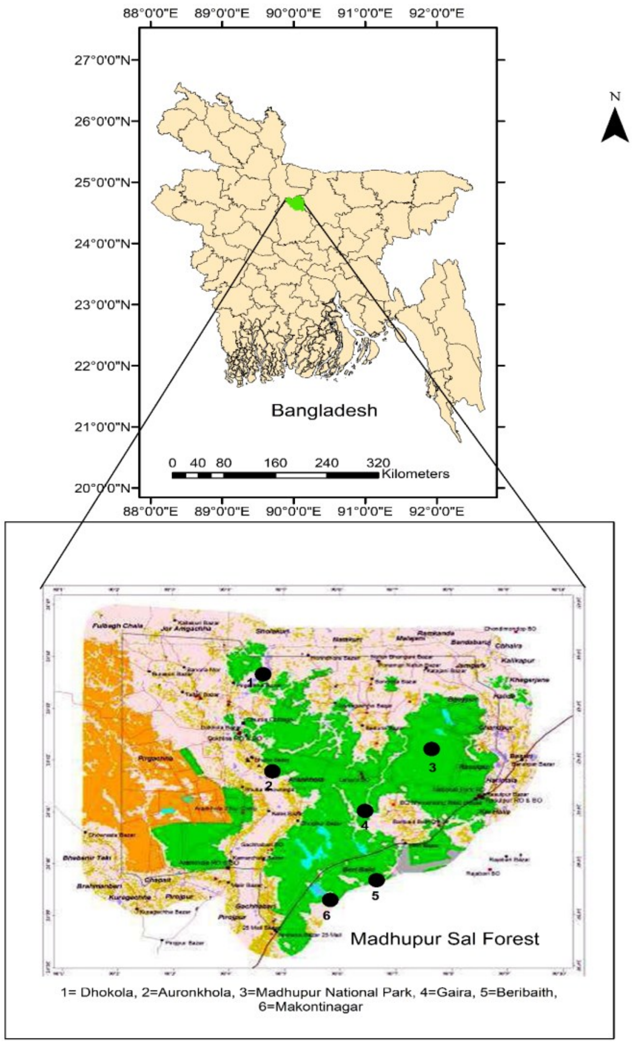

Figure 1. Map of the study area depicting Bangladesh and Madhapur Garh.

2.2. Data collection

The study area was deliberately chosen in Madhupur Upazila, Tangail district, due to the high concentration of the Garo community in this region. The Garo villages were collected from the Madhupur Upazila statistics office. The study selected seventy (70) Garo people from six villages. Data were collected by interview, a semi-structured questionnaire, focus group discussions (FGD), and direct observation from April to July 2023. Data were designed on the basis of demographic characteristics as follows:

(i) Age;
(ii) Education;
(iii) Family size;
(iv) Farm size.

Additionally, the organization of data on gender roles in agroforestry practices among Garo farmers was based on the following aspects:

(i) Perceptions of Garo men and women regarding agroforestry practices.
(ii) Gender roles in agroforestry activities within the Garo ethnic community.
(iii) Approaches adopted by the Garo community in agroforestry practices.
(iv) Sources of information accessed by Garo men and women.
(v) Decision-making processes in agroforestry management.
(vi) Challenges faced by the Garo community in adopting agroforestry.

2.3. Survey methods

The participants were chosen based on their involvement in agroforestry management within the selected villages of the study area. To identify suitable respondents for a detailed study, an initial socio-economic survey was conducted to assess key socio-economic parameters. A semi-structured questionnaire, prepared in advance and pre-tested for clarity, was used for the survey, allowing respondents to freely express their opinions on each topic.

The collected data comprised: Primary data, including respondents' identity details (name, gender, age, farm size, and annual income), along with their gender-specific roles in agroforestry activities such as land preparation, planting, fertilizing, weeding, woodlot collection, harvesting, transportation, and marketing.

(i) Secondary data, derived from gender-related literature, with primary data obtained through direct questioning and secondary data gathered from literature reviews.

Following individual interviews with farmers, focus group discussions (FGDs) were conducted in each village, involving 8–10 farmers per group. However, interviews and discussions alone were insufficient to gather all the necessary data, as respondents sometimes provided unclear or imprecise answers. Therefore, to gain a broader understanding of the socio-economic dynamics in the target villages, close observation and active participation in their daily activities were essential. Direct engagement allowed for the collection of real-life insights beyond verbal responses.

Special care was taken during data collection to minimize errors. Additionally, selected questions specifically addressed the gender roles of Garo farmers and the challenges they faced in adopting agroforestry management systems.

2.4. Compilation of data

Upon completion of the group discussions and interviews, the data collected from the interview schedule was organized, tabulated, and analyzed based on the study's objectives. During this process, local units were converted into standard units. The responses from the interview schedules were then transferred to a master sheet to simplify the tabulation process.

2.5. Analysis of data

The data collected from the study were organized and analyzed using Microsoft Excel and R Studio. Descriptive statistics, such as percentages and means, were employed to summarize the data. For inferential analysis, the Chi-square test was used to examine relationships between qualitative variables, while the independent t-test was applied to compare quantitative variables across different groups. These statistical methods were selected to ensure a thorough analysis and reliable interpretation of the results.

3. Results

3.1. Demographic characteristics of the farmers involved in agroforestry practices

3.1.1. Age

Age typically influences the viewpoints of the respondents. The results revealed that participants' ages varied from young to old (**Table 1**). The participants were categorized into three age groups: young (under 35 years), middle-aged (35–50 years), and old (above 50 years) (**Table 1**). Among the Garo participants, 37.2% fell into the older age group, while only 12.8% were in the young age category (P-value < 0.01) (**Table 1**). The findings also indicate that middle-aged individuals made up the largest proportion of participants, with 50% of the total. Age plays a significant role in farmers' likelihood of engaging in agroforestry. The results suggest that middle-aged farmers are more open to adopting agroforestry, a relatively modern production system in the study areas, compared to older farmers.

3.1.2. Education

The results indicated that a significant proportion of the Garo participants in the study area are illiterate (37.1%), with medium-level education (primary) at 22.7%, secondary education at 15.7%, and higher secondary education at 18.7%. The percentage of participants with graduate or higher education was very low, at 5.8% (P-value < 0.01) (**Table 1**). It is found that the participants who are graduates and above are not dependent on agroforestry for their livelihoods because they tend to government and non-government/NGOs jobs, business, nursing, etc. Despite these conditions, many Garo people are working to adopt agroforestry in an effort to improve their socioeconomic standing and develop revenue.

Table 1. Demographic characteristics of the farmers involved in agroforestry practices.

Characteristics	**Respondent**	
Participant's age	Number	Percent
Young (< 35)	9	12.8
Middle aged (35–50)	35	50
Old (> 50)	26	37.2
Education level	Number	Percent
Can sign only	26	37.1
Primary	16	22.7
Secondary	11	15.7
Higher secondary	13	18.7
Graduate and above	4	5.8

Table 1. (*Continued*).

Characteristics	**Respondent**	
Family Size	Number	Percent
Small (up to 4)	8	11.4
Medium (5–8)	53	75.8
Large (9 and above)	9	12.8
Farm Size	Number	Percent
Marginal (0.02–0.2 ha)	-	-
Small (0.21–1 ha)	47	67.2
Medium (1–3 ha)	21	30
Large (above 3 ha)	2	2.8

3.1.3. Family size

Regarding family size, the results clearly show that the family sizes of Garo participants are varied greatly, with (75.8%) of households having 5–8 individuals, indicating that the majority of the families are medium in size in terms of family members (**Table 1**). Only approximately (12.8%) live in large families having 9 or more individuals and (11.4%) are in small families having up to 4 individuals (P-value < 0.01) (**Table 1**). It was found that family size has the least impact on their livelihood choices because most individuals depend on agroforestry practices for their livelihood, regardless of how large or small their family is.

3.1.4. Farm size

The Garo participants were categorized into four groups based on their farm size. The results revealed that 30% of participants fell into the medium category, with farm sizes ranging from 1–3 hectares, while only 2.8% were in the large category with farms exceeding 3 hectares (**Table 1**). The majority of participants (67.2%) owned small land holdings, ranging from 0.21 hectares (P-value < 0.01) (**Table 1**). It was also observed that participants with small and medium-sized farms were more active and engaged in various agroforestry practices, such as tree planting, management activities, and fruit-based agroforestry.

3.2. Agroforestry practiced by the Garo community

The study found that fast-growing trees such as *Acacia auriculiformis* (Akashmoni), *Eucalyptus camaldulensis* (Eucalyptus), and *Azadirachta indica* (Neem), when paired with shade-loving crops like pineapple, aroid, turmeric, and ginger, were the most common agroforestry practices in both the Madhupur Sal forest and the study area. Additionally, the local Sal (*Shorea robusta*), Mahogany (*Swietenia mahogoni*), and Teak (*Tectona grandis*) trees, combined with shade-loving crops, were also observed in the study area (**Figure 2**).

Figure 2. Agroforestry practice by the Garo community.

3.3. Gender role in agroforestry management

The division of tasks between women and men reflected gender roles within the community. The study revealed that both genders were involved in the adoption and management of agroforestry. The gender distribution of respondents was 52.8% male and 47.2% female. According to the study's findings, agroforestry management activities such as land preparation, planting, fertilizing, and transportation were predominantly carried out by men. In contrast, women not only handled household duties but also participated in various agroforestry tasks, including pruning, weeding, mulching, and woodlot collection. Garo women have historically played a significant role in agricultural production, and as trees are part of this process, they manage and utilize them. The study also showed that Garo men and women often engaged in agroforestry practices together, performing tasks simultaneously.

3.4. Perceptions of Garo men and women in agroforestry practices

The study found a slight difference in the perceptions of males and females regarding agroforestry programs. The survey also explored how men and women prioritize agroforestry activities in their daily routines. The results showed that both genders placed a moderate to high level of importance on agroforestry (**Table 2**).

Table 2. Agroforestry program and its priority among Garo men and women.

Priority level	Male (n = 37)		Female (n = 33)	
	Number	Percentage	Number	Percentage
High	32	86.4	26	78.8
Moderate	5	13.6	7	21.2
Low	-	-	-	-

As shown in **Table 2**, among male respondents (37), 86.4% were categorized in the high-priority level, while 13.6% fell into the moderate category. In contrast, among female respondents (33), 78.8% were in the high-priority category, and 21.2% in the moderate category (P-value = 0.59). Notably, neither males nor females considered agroforestry a low priority. However, female respondents showed less interest in adopting agroforestry compared to their male counterparts, mainly due to limited access to inputs and technical knowledge.

In the focus group discussions (FGDs) held in the selected villages, both men and women expressed a desire to expand agroforestry practices, likely because the system was perceived as highly profitable. Participants utilized a variety of agricultural and tree species. Women preferred forest trees like Akashmoni (*Acacia auriculiformis*), a native timber species known for its fast growth and usefulness as fuelwood and fodder. In neighboring areas, this species provided better merchantable height and diameter, making it more profitable to sell. Meanwhile, men showed more interest in cultivating a wider range of crops. They preferred growing pineapple, followed by ginger, turmeric, and aroid, for short-term income.

3.5. Gender role in agroforestry activities of the Garo ethnic community

Table 3 presents details on the division of gender roles between men and women in crop and agroforestry production. According to both genders, many farming tasks are shared between men and women.

Women's participation in agroforestry activities is higher than men's in tasks such as weeding and collecting non-wood forest products, while men are more involved in activities like laying out the farm (95%), ploughing (78.8%) (P-value = 0.02), planting trees (78.8%), fertilizing (83.7%), and pruning (86.5%) (**Table 3**. According to male respondents, weeding (100%) and non-wood forest product collection (100%) are solely carried out by Garo women. In contrast, female respondents indicated that non-wood forest product collection is a shared task, with 15.2% done by both genders and 84.8% by women. Notably, a significant number of both men (51.4%) and women (69.6%) reported that packaging and marketing are joint activities, despite these tasks being considered challenging for women. However, weeding (100%) and non-wood forest product collection (84.8%) were generally seen as tasks predominantly handled by women (according to both genders) (**Table 3**). Women are also responsible for gathering fuelwood for daily cooking. Focus group discussions revealed that poultry raising, typically done by women, does not require much time from either gender. Although both men and women are actively involved in agroforestry, the survey and focus group discussions highlighted distinct roles for each gender in their participation.

Table 3. Gender roles of Garo men and women in agroforestry activities.

Activities	% reported by male			% reported by female		
	Male	Female	Both	Male	Female	Both
Land Preparation	95	-	5	87.8	-	12.2
Ploughing	67.5	13.5	18.9	78.8	15.2	6
Planting Trees	72.9	-	27.1	78.8	12.2	9
Fertilizing	83.7	-	16.3	81.8	12.2	9
Pruning	86.5	-	13.5	84.8	9.1	6.1
Weeding	-	100	-	-	100	-
NWFP	-	100	-	-	84.8	15.2
Packing and Marketing	48.6	-	51.4	15.2	15.2	69.6

3.6. Garo community approaches to agroforestry practices

The Garo community used various methods while practicing agroforestry. In **Table 4**, the most preferable approach was traditional knowledge (100%) (reported by both genders). Meanwhile, technical knowledge is more commonly used by male respondents (45.9%) compared to female respondents (6.1%). In the selected villages, some non-governmental organizations (NGOs) i.e., CARITAS, BRAC are actively working and implementing microcredit as well as other development programs. These NGOs programs usually focus on the agroforestry activities of men (89.2%) and women (69.6%), especially to build up their skills through training (**Table 4**). But women (30.4%) have less accessibility in the market, whereas men (94.6%) have more.

Table 4. Approaches by the Garo community in executing agroforestry practices.

Approaches	% According to male (n = 37)		% According to female (n = 33)	
	yes	no	yes	no
Traditional Knowledge	100	-	100	-
Technical Knowledge	45.9	54.1	6.1	93.9
Training (NGOs)	89.2	10.8	69.6	30.4
Market Access	94.6	5.4	30.4	69.6

3.7. Sources of information for Garo men and women

As illustrated in **Table 5**, training was the primary source of information on farming and tree management, with men (91.8%) and women (81.1%) participating actively. Additionally, focus group discussions (FGDs) served as another information source, with men (48.6%) using it more frequently than women (27.2%) (P-value = 0.43).

The data of **Table 5**, showed that Garo men and women rarely seek information from neighbors regarding agroforestry practices. Extension staff provide a lot of useful information; only 9.1% of women attended, and 16.2% were men. This clearly shows that both men and women in the study site have little exposure due to their low educational level, especially for women with a lack of technical knowledge.

Table 5. Sources of information for Garo men and women.

Sources	male (n = 37)				female (n = 33)			
	Yes	Per (%)	no	Per (%)	yes	Per (%)	No	Per (%)
Extensional Staff	6	16.2	31	83.8	3	9.1	30	90.9
Training	34	91.8	3	8.2	27	81.8	6	18.2
FGD	18	48.6	19	52.4	9	27.2	24	72.8
Neighbors	12	32.4	25	67.6	15	45.4	18	54.6

3.8. Decision-making in agroforestry management practices

Garo is traditionally a matrilineal indigenous community, with Garo women dominating the household based on their culture's decision-making. Although women have traditionally led the family, this trend has recently been reversed, i.e., women's dominant roles have been adjusted such that both males and females have equal rights to make decisions. The Garo community has begun to recognize the necessity of gender equity (equal rights of men and women) since they have moved out of numerous prejudices of their traditional culture and adopted modern concepts. According to the study, however, the majority of respondents (both men and women) shared decisions during agroforestry management. **Table 6** illustrates that both men and women make the majority of farming decisions jointly.

Respondents revealed that both men and women play a dominant role in making decisions regarding crop and variety preferences (80%) and seedling purchases (80%). Other activities like planting time (62.8%), time of applying fertilizer (61.4%), how much to sell from production (75.8%), given/taken lease (45.8%) (**Table 6**) are also decided by both genders in a family. But male respondents stated that in case of planting and fertilizing, most of the time they took decisions that raised the percentage to (34.4%), (28.6%) (P-value < 0.01) respectively compared to women. Because women have very little education as well as technical knowledge.

Table 6. Making decisions by Garo males and females in agroforestry management.

Statements	Male%	Female%	Both%
Crop/Variety Preference	10	10	80
Seedling Purchase	11.4	8.6	80
When to Plant	34.4	2.8	62.8
When to give Fertilizer	28.6	10	61.4
Sell from Production	11.4	12.8	75.8
Land Purchase/Lease	30	24.2	45.8

3.9. Problems in adopting agroforestry by Garo community

The Garo community relies significantly on agroforestry for various types of produce and multipurpose uses. In the studied area, Garo men and women collaborated on different farming activities. However, they encountered challenges that impeded their adoption of agroforestry. While both men and women faced difficulties, women experienced more significant challenges. The study provided valuable insights into the problems faced by Garo farmers.

Table 7. Challenges faced by Garo men and women in adopting agroforestry.

Problems	Male%		Female%	
	yes	no	yes	no
Lack of Technical Knowledge	48.6	51.4	87.8	12.2
Lack of Money	16.2	83.8	84.8	15.2
Lack of Labor	32.4	67.6	81.8	18.2
Difficult to Practice	16.2	83.8	60.6	39.4

According to **Table 7**, male and female participants pointed out challenges they faced such as a lack of technical knowledge (male 48.6% and female 87.8%), a lack of money (male 16.2% and female 84.8%), a lack of labor (male 32.4% and female 81.8%), and practice difficulties (male 16.2% and female 60.6%) (P-value < 0.01). These statistics clearly demonstrated that women faced challenges in practically a few sectors of agroforestry management. This is because of their lack of educational attainment, technical knowledge, time and labor, and communication skills. Although women appeared to be more engaged in agroforestry, they also looked to face more challenges than men.

4. Discussion

In Madhupur, banana agroforestry emerges as a more profitable option financially. However, research suggests that pineapple agroforestry holds promising ecological and economic potential due to its favorable ecological properties and lower initial investment requirements [14]. A major challenge in agroforestry planning is selecting the right species that meet the system's demands [15]. The findings indicate that the Garo community practices agroforestry with fast-growing trees like *Acacia auriculiformis* and *Eucalyptus camaldulensis*, in combination with shade-tolerant crops such as pineapple and turmeric, highlighting their reliance on species offering both ecological and economic benefits [6]. Agroforestry plays a vital role in enhancing food security, with both men and women actively participating. The findings reveal that men are mostly involved in tasks such as land preparation (95%) and tree planting (72.9%), while women play a significant role in activities like pruning (84.8%) and non-wood forest product collection (84.8%) [6]. However, women's involvement and benefits are restricted by cultural norms, lack of technical knowledge (87.8%), financial barriers (84.8%), and limited access to markets and labor resources [6,16]. Studies show that although agroforestry offers potential benefits for women, their participation is often more prominent in tasks traditionally considered as women's domain, such as collecting indigenous fruits and vegetables, rather than in commercially valued enterprises like timber production [17]. Despite relatively high participation in activities such as soil fertility management and fodder production, women's engagement is constrained by factors like land ownership and access to extension services [17]. Research indicates that women primarily manage trees on farms, especially in the early stages, emphasizing their vital role in agroforestry [18]. In addition to challenges related to a lack of technical know-how, women, especially from ethnic minority backgrounds, face compounded difficulties like limited access to land and labor resources, as noted by Catacutan and Naz [19]. This is consistent with the study findings, where women reported more challenges than men in adopting agroforestry, particularly in accessing labor and technical resources [6]. Despite these obstacles, rural women play an essential role in increasing household income through their active participation in various agricultural tasks, underscoring their indispensable contribution to the success of agroforestry, as highlighted by Hanum et al. [20]. Moreover, the diverse benefits of agroforestry, including its ability to provide a range of products at minimal costs, as emphasized by Kiptot [21], show promise in improving rural livelihoods. Recognizing the importance of inclusive participation, both genders must be actively engaged in agroforestry practices to maximize its benefits and ensure equitable access to productive resources, echoing the views expressed by Catacutan and Naz [19].

The study by Akther et al. [22] further explores gender-based disparities in decision-making within agroforestry, highlighting the distinct roles men and women take in specific tasks. This aligns with the findings, which show that decisions regarding planting times and fertilization are typically made by men (34.4% and 28.6%, respectively), while decisions about crop variety and seedling purchase are generally joint (80%) [6]. While men primarily oversee tasks like sales and land preparation, women mainly manage activities such as harvesting and processing. Despite their crucial role in maintaining the food system, gender imbalances persist at the household level, negatively impacting women's nutritional status, as noted by Ali and Niehof [23]. However, there are signs of progress, such as increasing female literacy rates and shifting kinship structures, indicating a gradual reduction in the gender gap. Yet, entrenched issues like dowry practices continue to pose challenges to achieving gender equity and inclusive development within agroforestry communities, highlighting the ongoing need for concerted efforts to address these systemic inequalities [23]. Despite women's active involvement, their engagement is hindered by a lack of technical knowledge, financial constraints, and limited access to markets and resources. This study underscores the importance of promoting gender equality by removing barriers to women's full participation. Recommendations include increasing women's access to training, technical knowledge, and financial resources, as well as encouraging their participation in decision-making processes. These measures could help reduce disparities and empower women in agroforestry practices. Additionally, this research fills gaps in understanding the gender dynamics of agroforestry adoption, illustrating how cultural norms, resource limitations, and joint decision-making shape gender roles within the Garo community.

5. Conclusion

This study emphasizes the significant role of gender dynamics in the adoption and management of agroforestry, offering important insights for the global community to address gender disparities in sustainable agricultural systems. The findings show that while both men and women are actively involved in agroforestry, their roles are clearly differentiated, with men handling more physically demanding tasks, while women play a key role in pruning, weeding, and resource collection. Despite this, women face greater challenges, such as limited access to technical knowledge, financial resources, and markets, which hinder their full participation and benefits from agroforestry practices.

To ensure both genders benefit equally, it is crucial to implement gender-sensitive policies and programs in agroforestry development. We recommend enhancing women's access to technical training, financial support, and market opportunities through targeted initiatives. Collaborative efforts involving governments, NGOs, and local communities should focus on promoting inclusive decision-making, joint resource ownership, and addressing structural barriers such as cultural norms and unequal resource distribution. By recognizing and empowering women's contributions, agroforestry systems can improve livelihoods, ensure equitable benefits, and foster sustainable development. These findings highlight the need for global efforts to prioritize gender equality in agroforestry, paving the way for more inclusive and resilient agricultural landscapes.

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Article

Revisiting the pollution-haven vs. porter hypotheses: Empirical evidence from Nigeria

Emmanuel T. Ideba[1], Anthony Orji[2,*], Onyinye I. Anthony-Orji[2], Jonathan E. Ogbuabor[2], Chukwuebuka Jude Chiobi[2], Chineze Hilda Nevo[2], Jude O. Ikubor[3]

[1] Department of Economics, University of Lethbridge, Lethbridge AB T1K 3M4, Canada
[2] Department of Economics, University of Nigeria, Nsukka 410105, Nigeria
[3] Department of Economics, Nigerian Defence Academy Kaduna, Crock 800283, Kaduna State, Nigeria
*** Corresponding author:** Anthony Orji, anthony.orji@unn.edu.ng

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Abstract: Since the 1970s, the role of trade liberalization and foreign direct investment in promoting environmental sustainability has been a hot topic in academics. While some research supports the Porter hypothesis, others support the pollution-haven hypothesis. Accordingly, this study aims to determine whether the pollution haven hypothesis holds by examining how trade openness and foreign direct investment affect Nigeria's environmental sustainability for the period of 1981 to 2021. By deploying the dynamic ordinary least square (DOLS) estimation technique, the study outcomes indicate that trade openness and foreign direct investment have a negative and significant long-term effect on Nigeria's greenhouse gas emissions. Therefore, the results of this study support the Potter hypothesis, which holds that emerging nations become centers of advanced and cleaner technology as a result of trade liberalization and foreign direct investment. As a result, the study suggests that the Nigerian government should support the creation of compressed natural gas (CNG) stations and the switch to CNG-powered vehicles. The Nigerian government can also promote investment in the green energy industry by offering tax holidays and other benefits to companies in this field. Furthermore, there should be a widespread public education campaign on the threat posed by global warming and the necessity of planting trees to mitigate the effects of climate change and discourage tree-cutting.

Keywords: trade; environment; foreign direct investment
JEL Codes: F18; F21; P33

1. Introduction

The impact of trade liberalization and foreign direct investment on environmental sustainability has been hotly debated since the 1970s [1]. While some researchers support the Porter Hypothesis (PH), others argue for the Pollution Haven Hypothesis (PPH). The debate intensified in the 1990s as a result of the establishment of organizations that promoted trade openness, including the World Trade Organization (WTO), the United Nations Conference on Environment and Development (UNCED), the Uruguay Round of the General Agreement on Tariffs and Trade, and the North American Free Trade Agreement (NAFTA) [2]. The school of thought that supported the pollution haven hypothesis claimed that because developed countries have strict environmental regulations, developing countries, which are known for their lax environmental policies, become hubs for pollution from trade and foreign direct investment. In the meantime, the school of thought that supports the Porter Hypothesis contends that stringent environmental regulations in developed nations benefit developing nations through trade liberalization and foreign direct investment as these nations become the destination for cleaner, more advanced technology that preserves the environment.

By definition, foreign direct investment (FDI) is the process through which a national investor acquires a sizable share in a company operating in another nation. Foreign direct investment, as opposed to stock market investments, concentrates on long-term investments in companies where the investor actively manages the business and owns at least 10% of the company's shares [3]. Conversely, trade openness quantifies the proportion of a nation's GDP that comes from its total imports and exports. Trade openness is essential for capital accumulation, knowledge transfer, and the diffusion of technology from industrialized to developing nations. Similarly, FDI plays an important role in stimulating the economic growth of a country through capital provided by international investors. FDI inflow promotes economic growth since it can increase the stock of real capital, enhance knowledge and technology transfer, and widen global commercial networks [4]. Over the last ten years, Nigeria has seen a notable decline in trade openness and foreign direct investment despite the crucial role that FDI and trade openness play in the prosperity of developing nations. **Figure 1** below illustrates how Nigeria's foreign direct investment (FDI) fell sharply after reaching an all-time high in 2011. Similarly, **Figure 2** below demonstrates that since reaching its peak in 2007, trade openness has been steadily declining.

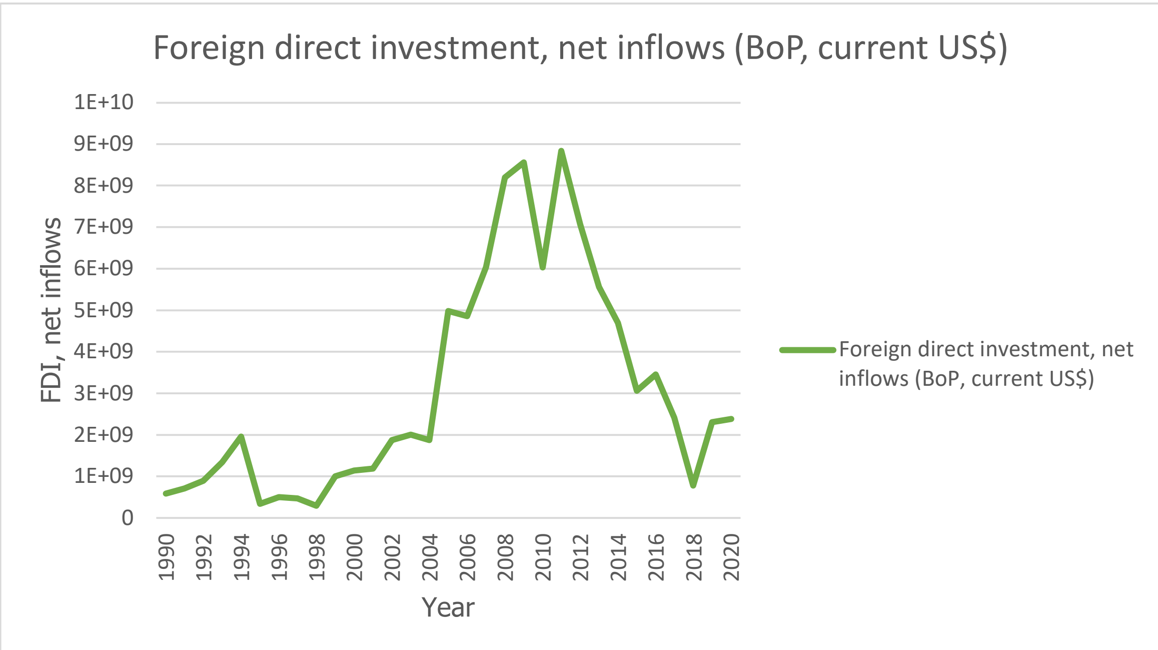

Figure 1. Foreign direct investment inflow in Nigeria.

Source: Authors' construct using data from World Development Indicators (WDI).

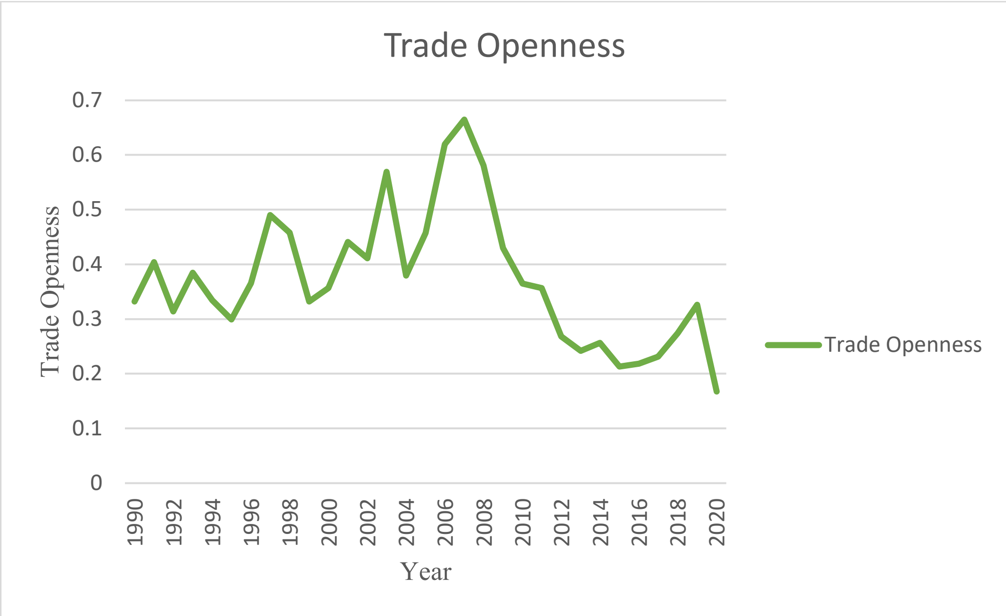

Figure 2. Trade openness in Nigeria.

Source: Authors' construct using data from World Development Indicators (WDI)

Research has yielded varying conclusions about the impact of foreign direct investment (FDI) and trade openness on environmental sustainability. Copeland and Taylor [5] submit that because of trade liberalization, companies that manufacture polluting goods have shifted from developed nations with strict environmental policies to developing nations with lax environmental regulations. This is because the comparative cost of pollution in these nations is less expensive. This movement turns emerging nations into sanctuaries—"pollution havens"—for polluting companies that manufacture noxious products. This perspective is supported by Riti et al [6], using the Auto Regressive and Distributed Lag (ARDL) model, validated the existence of the pollution haven hypothesis in Nigeria. The study's conclusions indicate that FDI inflow has a positive impact on Nigeria's CO_2 emissions. However, it is necessary to note that the reliance on aggregate national data may suffuse more nuanced regional or sectorial variations. For instance, Ayadi et al [7] also found evidence supporting the pollution haven hypothesis in Nigeria, while Ekesiobi [8] reported a more complex finding, suggesting the presence of the Porter hypothesis in Nigeria in the short run but a long-run pollution haven effect in Nigeria. Singhania and Saini [9] highlighted the importance of financial development and institutional quality in bridging the gap between FDI and environmental sustainability. The study suggests that institutional quality can facilitate the inflow of environmentally friendly technologies in the receiving country. Similarly, Yan et al [10] demonstrate that capital market liberalization leads to a substantial increase in the variability of ESG ratings across firms, suggesting a complex relationship between market openness and corporate sustainability practices. Hence, it is important to consider the dynamic impact of policy and institutional changes on the effectiveness of FDI on environmental sustainability, especially in developing countries like Nigeria.

According to the Federal Environmental Protection Agency (FEPA), Nigeria is fully dedicated to implementing the National Environmental Policy, which is designed to achieve sustainable development to address the environmental difficulties it faces.

The policy's objectives include the preservation of natural resources and the protection of the environment [11]. Also, Nigeria unveiled the National Renewable Energy and Energy Efficiency Policy (NREEEP) in 2015. This initiative hopes to reach a capacity of over 23 GW for renewable energy by 2030. Nigeria approved a National Action Plan in 2019 that included several emission-reduction initiatives. The strategy is centered on lowering methane emissions from natural gas transportation and oil production leaks. Furthermore, in November 2021, Nigeria enacted the Climate Change Act, whose main goal is to reduce greenhouse gas emissions in the nation by establishing a framework that will allow for the achievement of net zero emissions between 2050 and 2070 [12]. However, data from **Figure 3** below demonstrates that Nigeria's carbon dioxide emissions reached an all-time high in 2019 following a decade-long upward trend.

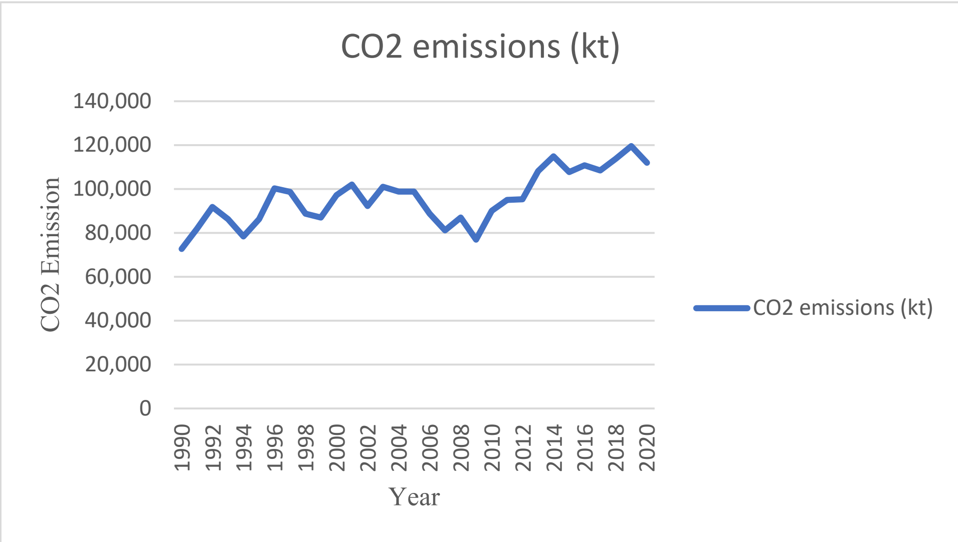

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Figure 3. CO_2 emission in Nigeria.

Source: Authors' construct using data from World Development Indicators (WDI)

In light of this unfavorable tendency, this study aims to add to the empirical discussion regarding the major impact that trade openness and foreign direct investment have on Nigeria's environmental sustainability within the context of the pollution haven hypothesis. The novelty of this study lies in its specific focus on the most recent decade of data for Nigeria—a period marked by significant fluctuations in FDI and trade openness, as presented in **Figures 1** and **2**. By focusing on more up-to-date data and employing a dynamic methodological approach, this study explicitly analyzes the evolving nature of the environmental impacts of trade openness and FDI in Nigeria. The remainder of this paper is organized as follows: Section 2 discusses the literature review, Section 3 examines the methodology, Section 4 presents the results and discussion, while Section 5 concludes and provides policy recommendations.

2. Literature review

Three key concepts in the study are environmental sustainability, foreign direct investment, and trade openness. There are several appropriate definitions for each of these concepts. We shall investigate what principles they uphold.

Environmental sustainability refers to the ability to efficiently make use of the earth's resources and maintain the ecosystem for current and future needs. Environmental sustainability is a conservation concept that emphasizes serving the needs of both current and future generations for resources and services without causing harm to the ecosystem that makes them available [13]. Environmental sustainability encompasses both location-specific and global concerns. Whereas soil erosion, air pollution, and water pollution are among the location-specific concerns, greenhouse gas emissions and climate change are generally associated with global issues [14].

Meanwhile, trade openness measures the proportion of a nation's GDP that comes from its total imports and exports. According to the United Nations [15], trade openness describes how a nation's economy is oriented (either inward or outward). It gauges a country's propensity to be open to commerce with other countries. Trade openness influences the environment through economic growth [16]. Countries that open their borders to international trade see a surge in demand for their commodities, which forces manufacturers to use a lot of polluting energy to produce enough items to meet demand. Nonetheless, the detrimental effects of economic expansion on environmental sustainability are not permanent. Eventually, as the economy grows and more people want a cleaner environment to maintain their quality of life, environmental sustainability will follow.

Furthermore, foreign direct investment (FDI) is the process through which a national investor acquires a sizable share in a company operating in another nation [3]. In other words, foreign direct investment is the total amount of money coming into a country's economy from foreign investors. In contrast to investments in a country's stock market, foreign direct investment focuses on long-term investments in businesses where the investor holds at least 10% of the company's shares and is actively involved in the management of the business. The strength of the environmental policies in the host and receiving countries helps to understand how foreign direct investment affects the environment. Some researchers will contend that developing countries frequently become the home of dirty goods due to foreign direct investment and the strict environmental policies of advanced nations, while others will contend that, as a result, emerging countries will become a destination for clean technology.

2.1. Trade openness theories

2.1.1. Comparative advantage theory

David Ricardo proposed this theory in 1817 in the Principles of Political Economy and Taxation. According to the notion, a nation ought to focus on producing and exporting the commodities and services that have the lowest opportunity costs. In other words, a nation ought to focus on producing commodities and services in which it possesses a comparative advantage over its peers. David Ricardo used this argument to refute the protectionist Corn Law of Great Britain, which prohibited the importing of wheat between 1815 and 1846. David Ricardo highlighted the advantages of trading with one another while arguing in favor of free trade.

2.1.2. Heckscher-Ohlin model

Eli Heckscher first proposed this hypothesis in 1919, and his student Bertil Ohlin developed it in 1933. The theory states that countries should export goods for which they have an abundance of the resources needed for production and import goods for which their domestic resources are limited. For example, nations possessing an abundance of labor should prioritize exporting labor-intensive goods and importing capital-intensive goods, whereas nations possessing an abundance of capital should prioritize exporting capital-intensive goods and importing labor-intensive goods.

2.2. Foreign direct investment theories

2.2.1. Market imperfections theory

Market imperfection theory is also known as market failure theory. The theory states that market imperfection attracts foreign direct investment. Market imperfections occur when the market violates the assumption of perfect competition as described by neoclassical economists. The primary assumption of the neoclassical economist is that the market will efficiently allocate resources. When this proves to be untrue, the market is said to have failed. Market imperfection can be a result of the number of buyers or sellers, heterogeneity of products, barrier to entry, and information asymmetry, among others.

2.2.2. Eclectic paradigm (OLI framework)

This theory was developed by British economist J.H Dunning. The theory explains the attractiveness of making foreign direct investments from the perspective of ownership, location, and internalization. The theory assumes that companies are more likely not to proceed with foreign direct investment if they can acquire the service needed for production internally and at a lower cost.

2.3. Environmental sustainability theories

2.3.1. Sustainable development theory

This theory was popularized by the Brundtland Commission's "Our Common Future" in 1987. According to the theory, long-term well-being can be achieved through striking a balance between economic growth, social justice, and environmental sustainability. The theory opposes the traditional approach to development, which often leads to economic imbalance, social injustice, and environmental degradation. Sustainable development theory proposes a more holistic approach to development, which encompasses social justice, economic growth, and environmental sustainability.

2.3.2. Ecological modernization theory

Ecological modernization is an approach that believes that environmental problems can be resolved through political, economic, and technological means in a given institutional framework, power structure, and continued economic growth [17]. According to the theory, the modernization of the political institution towards making the economy environmentally friendly and the transformative role of technology, innovation, and market dynamics is imperative in addressing environmental issues.

2.4. Empirical literature

2.4.1. Time series outcomes

Solarin et al [18] investigated the existence of the pollution haven hypothesis in Ghana by employing the autoregressive distributed lag (ARDL) model. The study's findings reveal that the pollution haven hypothesis is not present in Ghana. In a different study, Zubair et al [19] utilized the autoregressive distributed lag (ARDL) model to investigate the relationship between GDP, FDI, capital, and carbon emission in Nigeria. According to the study findings, GDP, FDI, and capital reduce carbon emissions in Nigeria. Similarly, Usman and Manap [20] investigated the influence of FDI and activities of multinational companies on sustainability in Nigeria by employing the autoregressive distributed lag (ARDL) model. The study's finding shows that foreign direct investment negatively influences carbon emissions in Nigeria.

Furthermore, the effect of international trade and foreign direct investment on carbon emissions in Nigeria was studied by Ekesiobi [8]. Using the autoregressive distributed lag (ARDL) model, the study found that foreign direct investment and international trade had a long-term positive impact on carbon emissions. The study did find, however, that short-term carbon emissions are adversely impacted by international trade and FDI. By employing the autoregressive distributed lag (ARDL) model, Riti [6] examined the relationship between FDI, manufacturing output, and environmental pollution in Nigeria. According to the findings of the study, the pollution haven hypothesis exists in Nigeria. In another study, Yakubu and Musah [21] employed the fully modified least squares (FMOLS) model to investigate the relationship between FDI and environmental pollution in Ghana. The study finding validates the pollution haven hypothesis in Ghana.

In a more recent study, Shen [22] explored the nexus between climate investment, green finance, and sustainable development in China using the coupled coordination model. The study's findings indicated that climate investment, when coupled with green finance, promotes sustainable growth. However, the effectiveness of these mechanisms varies across different regions, highlighting the need for proper climate investment and environmental policies. Other studies that also adopted a time series approach to investigate the FDI nexus with other macroeconomic variables and found diverse results include [23–29].

2.4.2. Panel outcomes

Singhania and Saini [9] employed the generalized method of moments (GMM) and system-generalized methods of moments (Sys-GMM) to investigate the interplay between foreign direct investment, institutional quality, and environmental degradation in 21 developing and developed nations. The study found the presence of a pollution haven hypothesis in developing nations.

Furthermore, Gharnit [30] investigate the relationship between FDI and carbon emission in 54 African countries by employing dynamic panel analysis. The study findings validate the presence of the pollution haven hypothesis. Halliru et al. [31] investigated the existence of the pollution haven hypothesis in ECOWAS countries. The study employed the pooled mean group (PMG) estimation method and found the existence of the pollution haven hypothesis in the selected countries.

In a different study, Nathaniel et al [32] examined if the pollution haven hypothesis is present in coastal Mediterranean countries by utilizing quantile panel data analysis. The study's findings show that the pollution haven hypothesis does not hold in coastal Mediterranean countries. In another study, Ndiaye et al. [23] used pooled least squares, along with fixed and random effects models, to examine the link between FDI and CO_2 emissions across 41 African nations. Their findings indicated that the pollution haven hypothesis does not hold in this context. Similarly, Bouzahzah [33] employed the panel autoregressive distributed lag (PARDL) model to investigate the relationship between FDI and CO_2 emission in 40 African countries. The study also found the absence of the pollution haven hypothesis. Tiba and Belaid [34] investigated the relationship between foreign direct investment, trade openness, and environmental sustainability in 27 African countries. The study employed the Common Correlated Effects Mean Group (CCE-MG) model and found that foreign direct investment and trade openness reduce environmental pollution. Similarly, Abbas et al [35] investigated the connection between foreign direct investment (FDI), energy consumption, and institutional governance in the reduction of greenhouse gas emissions in a panel of Asian countries and found that foreign direct investment has a significant moderating role in the nexus between energy consumption and greenhouse gas emissions. In particular, the study highlighted that FDI inflows enhance the reduction of GHG emissions. Other studies that also adopted a panel approach to investigate the FDI nexus with other macroeconomic variables and found diverse results include [36–39].

Summarily, the majority of the studies reviewed (among others, see Zubair et al [19]; Yakubu and Musah [21]; and Riti et al [6]) focused on examining the relationship between FDI and environmental sustainability. Meanwhile, a few studies Ekesiobi et al [8] have jointly looked into the effect of FDI and trade openness on environmental sustainability in Nigeria. As a result, this study employs both FDI and trade openness as the core independent variable to validate the existence of the pollution haven hypothesis in Nigeria. Additionally, the majority of studies on Nigeria employed the autoregressive distributed lag (ARDL) estimating approach. However, in this study, the dynamic ordinary least squares estimate method (which is more robust against endogeneity problems and serial correlation) is employed. To the best of empirical knowledge, this is one of the few studies that made use of a more reliable measurement of environmental degradation (total greenhouse gas emissions) compared to the more restrictive measurement of GHG emissions by carbon emission used as a proxy for environmental degradation in other studies.

3. Methodology

3.1. Model construction

This study hinges on the pollution haven hypothesis, which states that global openness to trade and foreign direct investment has led to the creation of "pollution havens", which are countries with less stringent environmental laws. As a result of their weak environmental regulations and lower compliance costs, pollution-intensive industries relocate to these countries. The influx of polluting industries leads to higher natural energy consumption, potentially increasing the levels of greenhouse gas emissions.

On this background, following similar studies [1,20] this article proposes the following model to investigate the relationship between FDI, trade openness, and total greenhouse gas emissions in Nigeria:

$$\text{LTGE} = f\,(\text{FDI, TOP, FFE, LPOP}).$$

where:

LTGE = Log of total greenhouse gas emission, FDI = Foreign direct investment, TOP = Trade openness, FFE = Fossil fuel energy consumption, LPOP = Log population.

Total greenhouse gas emissions and population are logged due to the large scale of the dataset, which may be positively skewed and might deviate from the normal distribution. Consequently, these extreme values can be difficult to model and interpret. The log form of the variable presents a more direct interpretation in which a one-unit change in the independent variable leads to a percentage change in the dependent variable [40].

3.2. Econometric strategy

In order to achieve the objective of this study, a multivariate framework is employed. This involves the Dynamic Ordinary Least Squares (DOLS) method, following the approach developed by Saikkonen and Stock and Watson. The DOLS technique is selected for its ability to provide reliable estimates even with limited data, as well as its effectiveness in addressing potential endogeneity and autocorrelation when variables exhibit different orders of integration. This is achieved by incorporating both past and future values of the independent variables, effectively mitigating bias caused by feedback effects and serial correlation. The DOLS model can be specified as follows:

$$\text{LTGE}_t = \alpha_0 + \beta_1\text{FDI}_t + \beta_2\text{TOP}_t + \beta_3\text{FFE}_t + \beta_4\text{LPOP}_t + \beta_5\Delta\text{FDI}_t + \beta_6\Delta\text{TOP}_t + \beta_7\Delta\text{FFE}_t + \beta_8\Delta\text{LPOP}_t + \beta_9\Delta\text{FDI}_{t+1} + \beta_{10}\Delta\text{TOP}_{t+1} + \beta_{11}\Delta\text{FFE}_{t+1} + \beta_{12}\Delta\text{LPOP}_{t+1} + \beta_{13}\Delta\text{FDI}_{t-1} + \beta_{14}\Delta\text{TOP}_{t-1} + \beta_{15}\Delta\text{FFE}_{t-1} + \beta_{16}\Delta\text{LPOP}_{t-1} + v_{t..}$$

where:

β_1, β_2, β_3, and β_4 = Long-run co-efficient.

B_5, β_6, β_7, β_8, β_9, β_{10}, β_{11}, β_{12}, β_{13}, β_{14}, β_{15}, and β_{16} = Nuisance Parameters.

Δ and v_t = Difference operator & Error term, respectively.

3.3. Data sources and variable descriptions

This study will focus on and be limited to the borders of Nigeria. The dataset for this analysis covers the period 1981–2021. Data on total greenhouse gas emissions, foreign direct investment, trade openness, fossil fuel energy consumption, and population were sourced from the World Bank World Development. Outlined in **Table 1** below are the operational descriptions of the respective variables:

Table 1. Variables description and sources of Data.

Variables	Description	Unit	Data Source
Total Greenhouse Gas Emissions (TGE)	It includes emissions from sectors like energy, industry, agriculture, land use, and waste. This variable standardizes the measurement of various greenhouse gases by converting them to their equivalent warming potential relative to CO_2.	Measured in metric tons of carbon dioxide equivalent (CO_{2e})	World Development Indicator Database
Foreign Direct Investment (FDI)	Foreign Direct Investment (FDI) represents the net flow of capital into a country, specifically to gain a sustained controlling interest in a business operating within that economy. This typically involves an investor acquiring at least 10% of the voting shares. FDI encompasses various financial components, including equity investments, reinvested profits, and other long-term and short-term capital, as reflected in a nation's balance of payments.	Measured in billions as a percentage of GDP	World Development Indicator Database
Trade Openness (TOP)	This reflects the degree to which a country participates in international trade and is commonly measured as the sum of exports and imports of goods and services, expressed as a percentage of Gross Domestic Product (GDP).	Measured in billions as a percentage of GDP	World Development Indicator Database
Fossil Fuel Energy Consumption (FFE)	Fossil fuel energy consumption measures the amount of energy derived from fossil fuels, such as coal, oil, and natural gas, expressed as a percentage of total energy consumption.	Measured as a percentage of total energy consumption	World Development Indicator Database
Population (POP)	Population refers to the total number of people living within a defined geographic area at a specific point in time.	Measured in millions	World Development Indicator Database

4. Empirical results

4.1. Descriptive statistics

To provide a foundational understanding of the data employed in this analysis, this section presents descriptive statistics, which offer a concise summary of the key characteristics of each variable, including measures of central tendency, dispersion, and shape. **Table 2** below presents a preliminary overview of the dataset before the subsequent findings of the study are further discussed.

Table 2. Descriptive statistics.

Statistic	TGE	FDI	TOP	FFE	POP
Mean	271,984.70	1.476171	0.404839	19.50043	1.33×10^8
Median	263,368.00	1.087951	0.364938	18.95003	1.26×10^8
Maximum	332,247.00	5.790847	1.067601	22.84479	2.13 E $\times 10^8$
Minimum	233,668.60	0.183822	0.162482	15.85414	75,175,387
Std. Dev.	24,471.20	1.235819	0.181654	1.538227	41,471,452
Skewness	0.9373	1.766764	1.600965	0.301549	0.374437
Kurtosis	2.87172	6.193077	6.214836	2.740056	1.924503
Jarque-Bera	6.031405	38.74765	35.17036	0.736799	2.934071
Probability	0.049011	0.00000	0.00000	0.691841	0.230608
Sum	11,151,374	60.52301	16.59841	799.5177	5.46×10^9
Sum Sq. Dev.	2.40×10^{10}	61.08993	1.31993	94.64569	6.88×10^{16}
Observations	41	41	41	41	41

Source: Authors' compilation from EViews' output.

Table 2 provides a summary of the data used in this study, covering 41 observations. It presents key descriptive statistics for the dataset employed in this study. The mean values indicate the average levels for each variable. For instance, the average TGE is approximately 271,984.70. The median, which represents the middle value, is close to the mean for all of the variables, suggesting that the data is relatively symmetrical and not influenced by outliers. This implies that the observations for each variable are generally clustered around the average during the observation period. The skewness values indicate the shape of the data distribution, and all the variables observed are positively skewed. The Jarque-Bera statistic and its associated probability are used to test for normality. In this case, TGE, FDI, and TOP have probability values below 0.05, suggesting that their distributions are not normally distributed. FFE and POP have probability values above 0.05, suggesting that their distributions are normally distributed. The table also provides the minimum and maximum values, showing the range of observations—the difference between the highest and lowest values in the dataset. The standard deviation, which measures the dispersion of the data, is also presented, indicating the variables have some variations.

4.2. Unit root test

To assess the stationarity of the variables, this study employs the Augmented Dickey-Fuller (ADF) test, outlined in **Table 3** below. Stationarity refers to the stability of a variable's mean and variance over time. The Augmented Dickey-Fuller test will be applied to find the unit root in this study. The proposed hypothesis will be:

H_0: The variable is not stationary.

H_1: The variable is stationary.

If the ADF test statistic exceeds the critical value at the 5% significance level, the null hypothesis of non-stationarity is rejected.

Table 3. Augmented Dickey-Fuller test for unit root.

Variables	ADF test statistic	*t*-Statistic	*P*-value	Order of integration	Decision
LTGE	−6.415557	−2.938987	0.0000	I(1)	Stationary
FDI	−3.872159	−2.936942	0.0049	I(0)	Stationary
TOP	−4.133648	−2.936942	0.0024	I(0)	Stationary
FFE	−6.537480	−2.938987	0.0000	I(1)	Stationary
LPOP	−3.002233	−2.963972	0.0461	I(1)	Stationary

Source: Authors' construct using E-Views' output. Note: Test critical values at a 5% level of significance.

The DOLS model's flexibility in applying when its variables have mixed orders of I(0) and I(1) is one of its primary advantages. The results of the ADF's unit root test, shown in **Table 3** above, show that, except for FDI and TOP, which are stationary at levels, i.e., I(0), others became stationary after differencing them once, i.e., I(1). Regardless of this mix of integration orders, the Johansen co-integration test in section 4.2 below revealed at least one cointegrating vector, confirming the existence of a long-run relationship among the variables. This further justifies the use of the DOLS model. It is also worth noting that an ARDL bounds test approach could also be adopted in this context. Nevertheless, given the established co-integration through the

Johansen co-integration test, the use of the DOLS model remains a robust and appropriate technique for the estimation of the long-run coefficients in this study.

4.3. Co-integration test

To determine the presence of long-run relationships among the variables, this study employs the Johansen co-integration test. Co-integration analysis assesses whether variables exhibit a stable equilibrium relationship over time, rather than simply moving together due to short-term fluctuations. The underlying hypotheses are as follows:

H_0 = There is no stable long-run relationship.

H_1 = There is a stable long-run relationship.

If both the trace and Max-eigenvalue tests indicate the presence of at least one co-integrating equation at the 5% significance level, the null hypothesis of no co-integration is rejected.

Decision: From **Tables 4** and **5**, the results indicate the presence of at least one co-integrating equation, as both the trace and Max-eigenvalue statistics exceeded their respective critical values in at least one instance. Consequently, the null hypothesis of no co-integration is rejected at the 5% significance level, suggesting a long-term relationship among the variables. This implies the variables tend to move together over time.

Table 4. Johansen co-integration test results (trace).

Hypothesized No. of Co-Integrating Equation	Eigenvalue	Trace Statistic	0.05 Critical Value	*P*.Value
None*	0.780850	104.6305	69.81889	0.0000
At most 1	0.372007	45.42856	47.85613	0.0831
At most 2	0.320921	27.28477	29.79707	0.0949
At most 3	0.258365	12.19105	15.49471	0.1480
At most 4	0.013600	0.534041	3.841466	0.4649

Trace test indicates 5 co-integrating eqn(s) at the 0.05 level. * denotes rejection of the hypothesis at the 0.05 level.

Table 5. Johansen co-integration test results (Max-eigenvalue).

Hypothesized No. of Co-Integrating Equation	Eigenvalue	Trace Statistic	0.05 Critical Value	*P* Value
None *	0.780850	59.20193	33.87687	0.0000
At most 1	0.372007	18.14380	27.58434	0.4832
At most 2	0.320921	15.09372	21.13162	0.2824
At most 3	0.258365	11.65701	14.26460	0.1242
At most 4	0.013600	0.534041	3.841466	0.4649

The Max-eigenvalue test indicates 3 co-integrating eqn(s) at the 0.05 level. * denotes rejection of the hypothesis at the 0.05 level.

4.4. Estimation result

In **Table 6**, the DOLS result demonstrates that in the long run, foreign direct investment (FDI) reduces total greenhouse gas emissions by an average of 2.29%. As a result, while controlling for all other variables, an increase in foreign direct investment will result in a 2.29% reduction in Nigeria's overall greenhouse gas emissions. This finding aligns with the Porter Hypothesis, which posits that stringent environmental regulations in developed nations can benefit developing nations through trade liberalization and FDI, as these nations become destinations for cleaner, more advanced technology. The likely explanation for this result is that FDI facilitates the inflow of foreign capital and, consequently, cleaner, more sophisticated environmental preservation technology. This finding is consistent with findings from Zubair, Samad, and Dankumo [20] and Usman and Manap [21], which also revealed that FDI contributes to environmental sustainability in Nigeria. This, however, contrasts with studies that found Pollution Haven effects, such as Riti et al [6], Ayadi et al [7], which suggested that FDI increases CO_2 emissions in Nigeria due to lax environmental policies. By intuition, this result suggests that there are improvements in Nigeria's policy environment, possibly due to initiatives like the National Renewable Energy and Energy Efficiency Policy (NEP) and the Climate Change Act of 2021, which may be enabling FDI to bring in cleaner technology. Furthermore, channeling FDI into green projects, as supported by green finance initiatives [22], could reinforce the outcome of the Porter Hypothesis in Nigeria. However, it is crucial to temper optimism, as simply increasing FDI is not a panacea. As Yan et al. [10] suggest, firms' environmental performance can diverge with liberalization, underscoring the importance of accompanying measures like robust environmental regulations and incentives.

Table 6. DOLS regression result.

Variable	**Coefficient**	**Std. Error**	***t*-Statistic**	***P*-Value**
FDI	−0.022897	0.007699	−2.973969	0.0072
TOP	−0.251174	0.073146	−3.433888s	0.0025
FFE	0.013410	0.005604	2.393216	0.0261
LPOP)	0.214210	0.024771	8.647615	0.0000
C	8.841666	0.496504	17.80783	0.0000
R-squared	0.914230	Adjusted R-squared		0.848881
F-statistic	13.99003	Prob(*F*-statistic)		0.00000
Durbin-Watson stat	2.049125			
Diagnostic Tests	Test Statistic		*P*-Value	
Heteroscedasticity Test (Breusch-Pagan-Godfrey Test)	13.54057		0.6329	
Autocorrelation Test (Breusch-Godfrey Serial Correlation LM Test)	3.146883		0.2073	
Specification Bias Test (Ramsey-Reset Test)	1.491638		0.2362	
Normality Test (Jarque-Bera Test)	1.008721		0.603892	

Source: Researcher's construct from EView's output.

Similarly, trade openness (TOP) has a long-run coefficient of −0.251174 and is statistically significant at a 5% significance level. As a result, holding other variables constant, a percent increase in TOP decreases total greenhouse gas emissions by 25.1174% on average. This finding is consistent with findings from Sun et al [40], who found that trade openness reduces environmental pollution in Nigeria. The most plausible explanation for this is that trade liberalization provides Nigeria with the opportunity to import cleaner energy sources.

In contrast, fossil fuel energy consumption upsurges total greenhouse gas emissions in Nigeria. The result from DOLS in **Table 6** shows that, on average, a percentage increase in fossil fuel energy consumption will increase total greenhouse gas emissions by about 1.34%, holding other variables constant. This explains the high rate of dependency on fossil fuel as the primary energy source for Nigeria's manufacturers and consequently the upsurge in total greenhouse gas emission in Nigeria. This finding aligns with Kojo and Paschal's [41] findings, who discovered that fossil fuel energy consumption contributes positively to environmental pollution in Nigeria.

Furthermore, an increase in population also influences GHG emissions positively. **Table 6** shows that in the long run, a percent increase in population will result in a 21.42% increase in total greenhouse gas emissions on average, holding other variables constant. This finding aligns with Schneider's [42] findings, which discovered that the population contributes positively to environmental pollution in Nigeria. Intuitively, the demand for manufactured consumer goods also grows as the population grows. As a result, fossil fuel consumption, a necessary input in the production process, grows. This leads to an increase in greenhouse gas emissions that contribute to environmental degradation.

The results of the diagnostic test show that the model is accurately specified, there is no serial correlation or heteroscedasticity, and the error term has a normal distribution.

4.5. Parameter stability test (CUSUM test)

The CUSUM test result shown in **Figure 4** below shows that all of the model's coefficients are stable over time since they are below the 5% critical bounds. We can trust the model's result based on the stability test result.

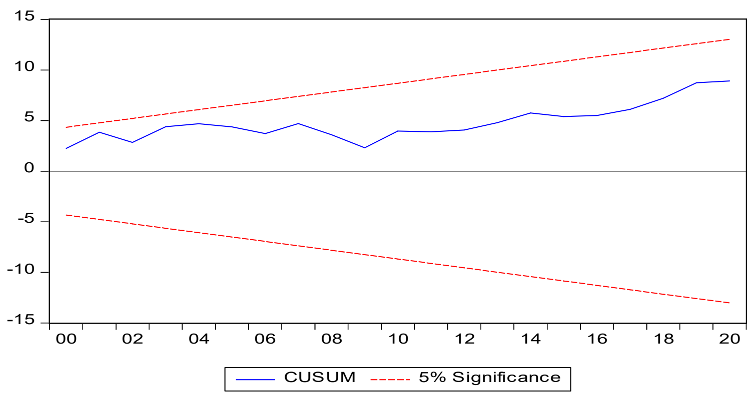

Figure 4. CUSUM plots for stability test.

5. Conclusion and recommendations

One major factor influencing a nation's economic growth is trade liberalization and foreign direct investment. Nonetheless, there is cause for concern regarding its impact on a nation's ability to preserve its environment. Hence, the purpose of this study is to critically assess how trade openness and foreign direct investment affect Nigeria's environmental sustainability within the context of the pollution haven hypothesis. The study's findings show that trade openness and foreign direct investment have a negative and significant long-term effect on Nigeria's greenhouse gas emissions. Therefore, the results of this study support the Potter hypothesis, which holds that emerging nations become centers of advanced and cleaner technology as a result of trade liberalization and foreign direct investment.

Consequently, given the findings of this study, which indicate that fossil fuel energy consumption increases total greenhouse gas emissions, this report suggests that the Nigerian government strongly supports the creation of compressed natural gas (CNG) stations and the switch to CNG-powered vehicles. Furthermore, to leverage the effect of FDI bringing in cleaner technology, as reinforced by the Porter hypothesis, the Nigerian government should actively promote investment in the green energy industry by offering tax holidays and other benefits to companies operating in this field. By attracting climate-focused investment and financing, Nigeria can solidify the positive environmental impact of FDI. Given the significant positive impact of population growth on greenhouse gas emissions, alongside the urgency of combating climate change, a widespread public education campaign on the threats posed by global warming is necessary in Nigeria. This is particularly vital because controlling emissions is not solely related to trade and FDI but also requires a well-rounded plan that tackles domestic factors.

This study contributes valuable insights to the ongoing debate regarding trade openness, foreign direct investment, and environmental sustainability. However, certain limitations should be acknowledged. The single-country focus restricts the generalizability of the findings; therefore, future research could adopt a comparative approach, examining a panel of countries with varying levels of economic development and environmental regulation. Moreover, given the significant impact of population growth on greenhouse gas emissions, public education campaigns addressing global warming are crucial alongside policies targeting trade and FDI.

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Review

Synergizing climate action: Integrating renewable energy, and biodiversity conservation for sustainable development

Emily Yohana[1,*], Fredrick Ojija[2]

[1] Department of Electrical and Power Engineering, College of Engineering and Technology, Mbeya University of Science and Technology, Mbeya 131, Tanzania
[2] Department of Earth Sciences, College of Science and Technical Education, Mbeya University of Science and Technology, Mbeya 131, Tanzania
*** Corresponding author:** Emily Yohana, mwalyagilecan@yahoo.com

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Abstract: Coordinated actions to protect biodiversity, incorporate renewable energy, and implement climate action are needed for sustainable development to be achieved in the context of global challenges like climate change, ecosystem destruction, and resource depletion. Climate action seeks to reduce the negative impact and strengthen the adaptive capacity of natural and human society. Climate action includes both adaptation and mitigation strategies. The transition to renewable power sources is of utmost importance to climate action because it helps to slow environmental degradation, curtail fossil fuel dependence, and significantly diminish greenhouse gas emissions. The adoption of renewable energy, such as solar, wind, and hydropower, is more environmentally friendly than conventional energy sources, but it may also pose potential risks towards biodiversity, so measures should be taken in planning to avoid negative environmental impacts. It is crucial to protect biodiversity around the world because it plays an important role in the delivery of ecosystem services such as soil fertility, pollination, water purification, and the sequestration of carbon that are vital to people's existence. In addition, strong ecosystems reduce the severity of climate change impacts, such as storms, droughts, and flooding. However, there may be trade-offs when striving for the increase of renewable energy and biodiversity conservation. Renewable energy development should always be complemented with biodiversity protection. This approach preserves the environmentally delicate ecosystems that are crucial to achieving climate action targets. The combination of climate action, renewable energy, and the need for biodiversity makes it possible to reap many benefits. These include stronger ecosystems and better human health, as well as economic growth and job creation. One example of such a nature-based solution is agrovoltaics, which combines solar energy production and farming. Restoring ecosystems, like forests or wetlands, can also greatly enhance carbon sequestration, reduce global warming, and protect endangered wildlife. This strategy aligns with international initiatives such as the United Nations Sustainable Development Goals (UN SDGs), specifically SDGs 7, 13, and 15. It serves as a building block towards a more sustainable future. Despite the clear possibilities of synergy, there are still barriers that must be tackled. Policy fragmentation, resource competition, and lack of inter-sector cooperation are some of the challenges that inhibit effective integration. Therefore, equitable governance and the adoption of nature-based techniques are essential.

Keywords: synergizing climate action; renewable energy; biodiversity conservation; sustainable development; ecosystem services

1. Introduction

As the world struggles with increasing temperatures, harsh weather, and the destruction of natural ecosystems, there has never been a more pressing need for climate action. One of the most urgent issues of our day is the connection between energy production, biodiversity loss, and climate change.

Sustainable development and biodiversity protection are closely related to the switch to renewable energy, which is crucial for reducing climate change. Countries must take into account the effects of energy infrastructure on ecosystems as they work to lessen their dependency on fossil fuels and slow down global warming. Among the main renewable energy sources are solar, wind, hydropower, and bioenergy; each has unique benefits for lowering reliance on fossil fuels and mitigating the effects of climate change on the planet's ecosystems [1].

Although renewable energy is a viable way to address the climate crisis, there are obstacles to its widespread use, especially when it comes to possible impacts on biodiversity. Pollination, carbon sequestration, water purification, and soil fertility are just a few of the vital ecosystem services that depend on biodiversity, which is the variety of life on Earth [2]. Therefore, maintaining biodiversity is crucial for ecosystem resilience, which in turn supports attempts to mitigate and adapt to climate change. However, if not properly designed and managed, large-scale renewable energy projects like hydroelectric dams, solar arrays, and wind farms can endanger species and ecosystems [3]. For instance, hydropower can change aquatic ecosystems by influencing water quality and fish migration, solar farms can destroy habitat, and wind turbines can kill birds and bats [4,5]

It is becoming clearer and clearer that there are substantial co-benefits to integrating renewable energy with biodiversity conservation as the globe moves toward more sustainable energy systems. Combining these two fields can boost economic growth, improve human health, and increase ecosystem resilience [6,7]. Reforestation and wetland rehabilitation, for instance, can improve biodiversity, restore damaged ecosystems, and guard against climate-related calamities like droughts and flooding in addition to sequestering carbon [8].

The Sustainable Development Goals (SDGs) of the UN emphasize how crucial it is to combine climate action with the preservation of biodiversity and the advancement of renewable energy. To achieve sustainable development, a comprehensive strategy is required, as highlighted by SDGs 7 (Affordable and Clean Energy), 13 (Climate Action), and 15 (Life on Land). To ensure that the transition to clean energy is both environmentally sustainable and socially equitable, biodiversity conservation must be incorporated into renewable energy laws and practices [9,10].

Notwithstanding this integrated approach's encouraging promise, there are still many obstacles to be addressed. Effective integration is frequently hampered by resource conflicts, policy fragmentation, and a lack of sectoral cooperation. For example, the development of renewable energy infrastructure in areas with high biodiversity value may collide with conservation priorities, resulting in environmental damage and land-use disputes [11]. Moreover, there are obstacles to the successful integration of both agendas due to the frequently misaligned regulatory frameworks that oversee biodiversity preservation and energy development. Innovative approaches are needed to address these issues, including the adoption of nature-based solutions, multi-sectoral cooperation, and the use of spatial planning tools. For instance, by maximizing land usage while preserving ecosystem health, agrovoltaics, which integrates solar energy generation with agricultural practices, has the potential to promote sustainable energy production and biodiversity conservation [12].

It is also imperative that the development of renewable energy be approached in a more egalitarian and inclusive manner. Climate change disproportionately affects vulnerable populations, especially those in developing nations, and they frequently encounter obstacles when trying to access renewable energy solutions. Achieving global sustainability goals requires making sure that these communities gain from climate resilience initiatives and renewable energy solutions [13,14].

A global strategy to combat climate change, advance sustainable development, and safeguard the environment must include the combination of biodiversity protection with the development of renewable energy. Enhanced environmental resilience, better public health, economic growth, and more social fairness are just a few advantages of this strategy. However, attaining these results necessitates overcoming major obstacles, such as the requirement for multi-sectoral coordination, policy fragmentation, and resource conflicts. We can build a more sustainable and just future for everybody if we encourage cross-sector collaboration, embrace nature-based solutions, and incorporate biodiversity concerns into renewable energy planning and policy. This study examines the benefits and drawbacks of combining biodiversity preservation with renewable energy, using case studies and existing research to illustrate methods for building a more low-carbon, sustainable future [15,16].

2. Literature review

In recent years, there has been a lot of interest in the connection between biodiversity conservation, renewable energy growth, and climate change mitigation. The demand for integrated strategies that strike a balance between conservation and renewable energy projects is growing as the urgency of addressing climate change and biodiversity loss increases on a global scale. The need for such harmonization is emphasized by the Sustainable Development Goals (SDGs), especially with regard to climate action (SDG 13) and the preservation of land and marine ecosystems (SDGs 14 and 15) [17].

Rising global temperatures, extreme weather events, and ecological disturbances are just a few of the negative environmental effects of climate change, which is mostly caused by human activity like the burning of fossil fuels and deforestation. To ensure long-term environmental sustainability, these issues require cross-sector coordination. In order to lower greenhouse gas emissions and lessen dependency on fossil fuels, renewable energy technologies like solar, wind, and hydropower are essential. To reduce ecological trade-offs, rigorous planning and regulatory interventions are necessary because the widespread implementation of renewable energy projects may have unexpected effects on biodiversity [18].

Simultaneously, by preserving vital functions like carbon sequestration, water purification, and food security, biodiversity conservation contributes significantly to improving ecosystem resilience. In addition to maintaining ecological stability, biodiversity protection is essential for maintaining human well-being in the face of climate change. Therefore, a holistic strategy that combines biodiversity preservation with renewable energy can greatly support sustainable development.

This literature review explores the evolving discourse on the intersection of renewable energy and biodiversity conservation. It highlights the opportunities and challenges of aligning these two crucial areas and examines policy recommendations that can facilitate a balanced approach. By synthesizing existing research, this review aims to provide insights into how renewable energy initiatives can be implemented while preserving biodiversity to foster long-term sustainability.

2.1. Synergies and challenges of integrating renewable energy and biodiversity conservation

The necessity of transitioning from fossil fuels to renewable energy such as solar, wind, hydroelectric, and geothermal power has gained significant recognition as a means to combat climate change. Nonetheless, the implementation of these technologies requires careful management to reduce adverse effects on biodiversity. As the shift towards sustainable energy sources intensifies, it is crucial to comprehend how renewable energy systems can be designed to simultaneously support climate health and biodiversity. The United Nations Sustainable Development Goals (SDGs) highlight the connections between renewable energy and biodiversity conservation. Specifically, SDG 7 promotes access to affordable and clean energy, while SDG 15 emphasizes the importance of terrestrial life; both goals encourage the incorporation of environmental factors into development approaches [19]. In this context, systems utilizing renewable energy can aid in the conservation of biodiversity by minimizing habitat loss and encouraging the restoration of ecosystems.

Table 1 lists technologies like solar, wind, and hydro, their positive and negative impacts on biodiversity.

Table 1. Summary of renewable energy technologies and their impact on biodiversity.

Renewable energy technology	Positive impacts on biodiversity	Negative impacts on biodiversity
Solar energy	Reduces carbon emissions, mitigating climate change.	Land use impacts (can disrupt habitats, especially in arid areas).
Wind energy	Clean, renewable energy.	Bird and bat mortality from collisions with turbines.
Hydropower	Provides renewable energy and water storage.	Disrupts aquatic ecosystems, migratory routes, and fish populations.
Geothermal energy	Provides low-carbon energy.	Potential land subsidence and disruption of local ecosystems.
Biomass energy	Reduces waste and offers renewable energy.	Can lead to deforestation and habitat destruction.

Additionally, the growth of renewable energy can be aligned with biodiversity initiatives through careful planning, environmental evaluations, and flexible management approaches. By integrating biodiversity aims with renewable energy projects, it is feasible to improve ecological health while delivering sustainable energy alternatives [17].

However, integrating renewable energy with biodiversity conservation presents several challenges, even though there is potential for beneficial interactions. To begin with, many renewable energy technologies, like large hydropower dams and wind turbines, can have harmful effects on local ecosystems. For example, hydropower initiatives have been shown to result in ecosystem flooding, disruption of migration patterns, and harm to fish populations. Similarly, the establishment of wind farms can pose risks to certain species of birds and bats [20].

Furthermore, the expansion results in an increased demand for land allocation that, in numerous cases, is threatened by land-use conflicts [21]. As identified, the majority of renewable power plants require wide expanses of their field, hence likely to overlap the biodiversity hotspots and critical habitats needed for the perpetuation of the vulnerable species as identified [22]. There are also energy-development versus biodiversity-protection trade-offs. Governance and policy frameworks also play a critical role in shaping the interaction between renewable energy and biodiversity. Weak policy enforcement, lack of coordination between sectors, and insufficient stakeholder engagement often hinder the effective integration of biodiversity conservation into renewable energy projects [23].

2.2. Policy frameworks and strategies

Policies are central to incorporating renewable energy and biodiversity conservation (**Table 2**). Internationally, agreements such as the Paris Agreement emphasize low-carbon energy transitions but also request the protection of biodiversity (**Table 2**). Translating these global commitments at both national and local levels involves well and robust policy frameworks that interlink both the needs of climate action and biodiversity conservation [24].

Table 2. Global and national policies linking renewable energy and biodiversity conservation.

Policy	Description	Impact on renewable energy and biodiversity	Source
Paris Agreement (2015)	Global framework for climate action and greenhouse gas reduction.	Encourages low-carbon energy solutions and mandates biodiversity protection in the context of climate action.	[25]
National Environmental Impact Assessments (EIA)	Requirement for assessments of potential environmental impacts of energy projects.	Ensures that biodiversity conservation is factored into energy development planning.	[26,27]
Green Finance and Green Bonds	Financial instruments designed to fund eco-friendly projects.	Promotes funding for renewable energy projects that include biodiversity safeguards.	[28]
UN Biodiversity Framework	A global strategy to protect and sustain biodiversity.	Encourages integration of biodiversity considerations into renewable energy projects.	[29]
Renewable Energy Standards	National targets for renewable energy adoption.	Can promote the growth of renewable energy but may need to be balanced with biodiversity protection measures.	[30,31]

National policies will have to react to the environmental impacts of renewable energy projects through responsible environmental practice and technology (**Table 2**). For instance, some countries carry out EIA on all new renewable energy projects so that biodiversity issues can be captured in the decision-making processes [31]. Other financial tools, such as green bonds and climate finance, also support biodiversity-friendly renewable energy project scale-up [32].

2.3. The role of technological innovation in synergizing renewable energy and biodiversity

Technological advancements can minimize the impacts of renewable energy on biodiversity (**Table 3**) [33]. Bird-friendly turbines improve wind turbine designs, and further advancement in solar panels helps to reduce negative environmental impacts [34]. More research is needed in finding better technologies to store energy with improved advanced batteries and management of grid systems to prevent the building of large hydropower dams that could endanger biodiversity [35]. The other aspect of essentiality involves the use of data and modeling tools in the assessment of biodiversity impacts by renewable energy projects. Such technologies would be informative for decision-makers regarding the ecological risks involved and enable adaptive management practices that reduce adverse outcomes (**Table 3**).

Table 3. Technological innovations in renewable energy and their impact on biodiversity conservation.

Technology	Innovation	Biodiversity Impact	Source
Bird-friendly wind turbines	Design modifications to reduce bird collisions.	Reduces bird mortality, improving ecosystem health.	[34,36]
Floating solar panels	Solar panel systems placed on water bodies to reduce land use.	Minimizes land disruption while providing clean energy.	[37]
Enhanced energy storage technologies	Improved battery technology and storage systems.	Reduces the need for large-scale hydropower dams, protecting aquatic biodiversity.	[38]
Solar panel recycling	Improved techniques for recycling solar panels at end-of-life.	Reduces e-waste and environmental degradation.	[39]
Ecological monitoring systems	Use of technology to monitor biodiversity impacts of energy projects.	Provides real-time data for adaptive management of renewable energy impacts on biodiversity.	[40]

2.4. Potential effects of synergizing renewable energy and biodiversity conservation

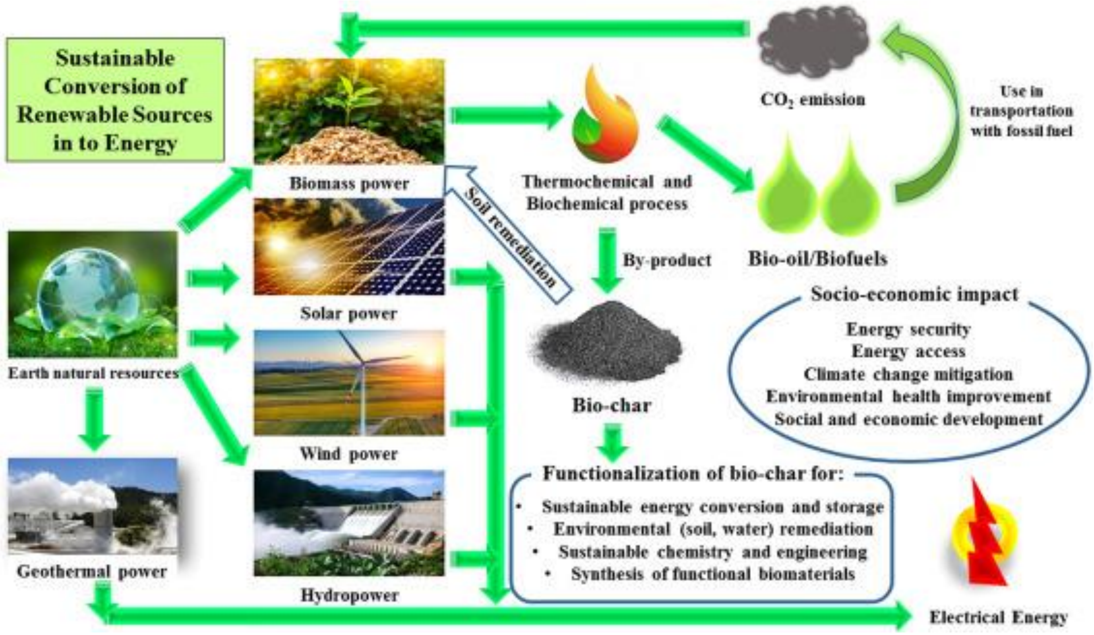

Figure 1. Sustainable conversion of renewable sources into energy: linking natural resources, energy production, by-products, and socio-economic impacts.

Synergizing climate action by integrating renewable energy and biodiversity conservation for sustainable development can have several potential effects shown in **Figure 1**.

2.4.1. Enhanced climate resilience and biodiversity protection

Both parties may have advantages when combined with renewable energy systems and biodiversity conservation measures. Because renewable energy sources like solar and wind generate little to no emissions, they lessen the negative effects of climate change on the environment. These renewable systems also contribute to the preservation of ecosystems and habitats that are essential for biodiversity by reducing the effects of climate change [30,41].

By reducing reliance on fossil fuels, renewable energy reduces pollution, habitat destruction, and resource depletion, all of which commonly threaten biodiversity. Protecting ecosystems from the adverse effects of climate change strengthens biodiversity conservation efforts [33]. Goals for Sustainable Development (SDGs). The accomplishment of several SDGs, including SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land), is aided by the integration of renewable energy with biodiversity conservation. While protecting ecosystems and ecological balance, integration aids in the advancement of sustainable energy use. By addressing energy demands and biodiversity conservation needs at the same time, policymakers can create frameworks that reduce trade-offs and pave the way for sustainable development [42].

2.4.2. Addressing trade-offs and balancing competing interests

If renewable energy installations are not taken into account during the planning stage, they may harm biodiversity. For instance, wind farms may force birds or other species to leave their habitats. Trade-offs can be turned into synergies, and detrimental effects on biodiversity can be reduced while maximizing beneficial contributions by planning energy resources sustainably, regionally, and with integrated environmental protection and safeguards (think rewilding projects, green corridors) [2]. Co-benefits are also encouraged by effective integration, as renewable energy infrastructure (like solar farms) may have two uses, like supporting land restoration initiatives or offering habitat for specific species [42].

2.4.3. Economic and social benefits

The financial advantages of combining biodiversity preservation with renewable energy, when carefully combined, renewable energy and biodiversity preservation can boost long-term economic stability and spur substantial economic growth. Particularly in areas with a wealth of natural resources, the switch to renewable energy sources like solar, wind, and hydropower offers significant potential for economic development. These industries have the potential to produce a number of immediate economic advantages, such as improved energy security, rural development, and job creation. One of the sectors with the quickest rates of growth in the world is renewable energy. The global workforce in renewable energy reached almost 12 million people in 2020, according to the International Renewable Energy Agency, and there is a great deal of room for growth as nations build out their renewable energy infrastructures to meet climate goals outlined in international agreements such as the Paris Agreement

[43,44]. This workforce offers a variety of jobs, from installing and maintaining renewable energy systems to producing solar panels and wind turbines. Furthermore, local economies can benefit from more job possibilities and better living standards by utilizing the potential of decentralized renewable energy projects, such as community-owned wind and solar farms, especially in isolated or rural locations [45]. Renewable energy projects can stop environmental deterioration and promote sustainable economic practices when they are planned with biodiversity protection in mind. For instance, as recommended, incorporating biodiversity evaluations into the planning and siting of renewable energy projects guarantees that the ecosystems' long-term economic value is not disregarded. Carefully thought-out renewable energy projects can offer ecosystem services and carbon sequestration, strengthening local economies' resistance to the effects of climate change [46]. Additionally, incorporating biodiversity preservation into the growth of renewable energy can lessen the dangers of environmental deterioration. By exhausting the very resources that enterprises depend on, unsustainable energy practices like habitat destruction and overuse of natural resources can impede economic progress. On the other hand, nations may protect the economic advantages of healthy ecosystems, such as clean water, rich soils, and pollination services, by making sure that energy systems are ecologically sound. The short-term expenses of incorporating biodiversity into energy projects may be greatly outweighed by the long-term cost benefits from these ecosystem services.

2.4.4. Public health and climate resilience

The combination of biodiversity protection with renewable energy has significant societal advantages in addition to financial ones, especially in the fields of social justice, public health, and climate resilience. By giving impoverished populations, especially those in developing nations, access to inexpensive, dependable, and clean electricity, the transition to renewable energy can aid in the fight against energy poverty [47,48]. Renewable energy provides a route to universal electricity access, which is essential for raising living standards, healthcare, and educational opportunities in underserved regions. According to the United Nations Development Programme, for example, off-grid locations without conventional energy infrastructure are best served by solar and wind energy. Furthermore, by empowering local communities and advancing gender equality, renewable energy initiatives can support social fairness. Women are disproportionately impacted by environmental deterioration and energy poverty in many areas. Women can become economically independent and take part in decision-making processes that influence their communities' futures by establishing employment possibilities in the renewable energy sector. Furthermore, local ownership and involvement options are offered by community-led renewable energy projects, which can improve social cohesion and boost community resilience to climate change [49]. Public health results can also be enhanced by incorporating biodiversity conservation into renewable energy systems. In contrast to fossil fuels, renewable energy sources don't contaminate the soil, water, or air. Less dependence on dirty energy sources like coal and oil can lead to cleaner air and fewer pollution-related illnesses, including cancer, heart disease, and respiratory disorders. Nature-based solutions, such as renewable energy projects that balance with local ecosystems, can lead to healthier environments and lower healthcare expenses, according to a study by the International Union for Conservation of Nature [20]. In terms of climate resilience, biodiversity preservation and renewable energy are essential for preparing for and lessening the effects of climate change. Renewable energy helps achieve the objectives of the Paris Agreement by lowering greenhouse gas emissions, a primary cause of climate change. By preserving natural buffers like wetlands, forests, and coral reefs, biodiversity conservation also aids ecosystems in adapting to climate change by shielding local communities from storms, flooding, and other climate-related effects. According to a UN Environment Programme study from 2023, integrated strategies that support the growth of renewable energy sources and biodiversity preservation might improve ecosystems' and communities' ability to adapt to climate-related disruptions [50].

2.4.5. Better services from ecosystems

Supporting ecosystem services: Vital services like pollination, water filtration, and carbon sequestration are provided by healthy ecosystems. These services are preserved through the expansion of renewable energy infrastructure and biodiversity conservation, which benefits society and the environment [51].

Ecosystem restoration: Initiatives for ecosystem restoration can incorporate some renewable energy projects, such as tidal or bioenergy, to improve biodiversity and meet energy demands [52].

2.4.6. International cooperation and innovative policies

International frameworks: Nations and international organizations can work together to develop creative policy frameworks that provide incentives for biodiversity preservation and renewable energy. International collaboration can advance funding sources, regulatory standards, and knowledge sharing [53]. According to integrating governance for the environment and energy, it can lead to cross-sectoral collaboration, bringing together the energy, conservation, agricultural, and urban planning sectors for sustainability at all levels: local, national, and international. Deploying renewable energy and conserving biodiversity together can have a positive impact on the environment, the economy, and society, leading to a more resilient and sustainable future. Our energy needs will be satisfied while preserving the very ecosystems that sustain life on Earth if climate action and biodiversity protection are combined.

2.4.7. Limitations of synergizing climate action, renewable energy integration, and biodiversity conservation for sustainable development

The move to renewable vitality sources and biodiversity preservation is essential to combating climate alter and accomplishing economic advancement objectives (SDGs). In any case, joining these endeavors presents critical challenges, as renewable vitality ventures frequently cross with biodiversity-rich regions, making clashes [54,55]. This survey investigates the major impediments in accomplishing cooperative energy among these basic goals, bolstered by inquiries about discoveries and case studies.

2.4.8. Arrive utilize clashes

Large-scale renewable vitality ventures require noteworthy arrival regions, leading to living space misfortune and fracture. For example, sun-based ranches in leave locales disturb environments by modifying soil composition, vegetation, and species intuitively. Wind ranches in meadows or coastal ranges have caused living space fracture, making it troublesome for species to get to their normal environments.

Renewable vitality establishments frequently compete with agrarian areas, affecting nourishment security. Sun-powered ranches, in specific, uproot beneficial rural areas, lessening trim yields. Adjusting renewable vitality development with the right prerequisites for horticulture and preservation may be a diligent challenge [56].

2.4.9. Biodiversity impacts

Wind turbines are notorious for their effect on winged creatures and bats. Transient feathered creatures and bats are exceedingly powerless to turbine collisions, which disturb population flow and environmental capacities [57].

Hydropower ventures modify oceanic biological systems by disturbing waterway streams, dredge transport, and angle relocation. For example, huge dams frequently piece transient angler species, driving to population decays and debilitating freshwater biodiversity [58].

2.4.10. Arrangement and administration challenges

Climate activity, renewable vitality, and biodiversity preservation approaches frequently work freely. The need for coordinate systems makes clashes between vitality improvement and preservation needs, particularly in nations with restricted regulation capacity [59].

Complex allowing forms delay the sending of renewable vitality ventures. Conflicting authorization of natural directions assists in complicating endeavors to adjust renewable vitality extension with biodiversity preservation.

2.4.11. Social value and resistance

Numerous renewable vitality ventures uproot nearby and innate communities. Huge dams and sun-powered ranches regularly constrain inhabitants to move without satisfactory stipends, abusing human rights and disturbing social legacy.

Renewable vitality ventures regularly come up short to lock in neighborhood communities within the arranging prepare. This need for a meeting leads to resistance, dissent, and delays in extended execution [60].

2.4.12. Financial and money related imperatives

Renewable vitality ventures with biodiversity-friendly plans regularly require higher introductory ventures. For instance, seaward wind ranches, which have less effect on earthbound biodiversity, are essentially more costly than coastal options.

Speculators see biodiversity-friendly renewable vitality ventures as hazardous due to vulnerabilities in directions and return on ventures. This limits the accessibility of subsidizing, especially in creating nations [61].

2.4.13. Innovative challenges

The transfer of renewable vitality foundations, such as sun-oriented boards and wind turbines, poses a critical Constrained reusing alternatives result in squander collection and potential contamination.

The need for biological information ruins the capacity to foresee and moderate the impacts of renewable vitality ventures on biodiversity. This data crevice complicates decision-making forms for venture organizers and policymakers [62].

2.4.14. Monitoring and compliance

Numerous renewable vitality ventures need strong observing frameworks to survey their impacts on biodiversity. This comes about in desperate need of moderation measures.

The requirement of natural directions is regularly conflicting, especially in low-income nations. Frail administration structures worsen this issue, permitting ventures to continue without appropriate adherence to biodiversity security guidelines [63].

2.4.15. Transient jumbles

Whereas the climate benefits of renewable vitality are prompt, the points of interest of biodiversity preservation are frequently long-term. This worldly disengagement makes challenges for adjusting short-term renewable vitality objectives with long-term preservation targets [33].

2.4.16. Climate alter criticism circles

Climate alteration modifies territories and species dissemination, complicating endeavors to preserve biodiversity close to renewable vitality establishments. For instance, shifts in transitory designs of fowls may increase their defenselessness to wind turbines [34].

2.4.17. Require for intrigue collaboration

Joining renewable vitality with biodiversity preservation requires collaboration among scientists, engineers, and policymakers. Be that as it may, a need for intrigue skills regularly hampers inventive arrangements.

Partner association, especially from inborn communities and preservation bunches, is basic but regularly neglected in renewable vitality arranging [64]. Synergizing climate activity, renewable vitality integration, and biodiversity preservation is basic for accomplishing maintainable improvement. Be that as it may, this integration faces critical challenges, including arrival-utilization clashes, biodiversity impacts, approach fractures, social resistance, monetary limitations, mechanical holes, frail observing frameworks, and climate-alter input circles. Tending to these restrictions requires a multifaceted approach, including strong approach systems, intriguing collaboration, mechanical development, and community engagement. By overcoming these obstructions, it is conceivable to form a feasible future that harmonizes vitality moves with biological conservation.

3. Conclusion

Probably, the incorporation of renewable energy and biodiversity conservation will be crucial for sustainable development. Challenges and trade-offs notwithstanding, successful case studies of policy frameworks have proved that integration can be done if proper planning and technological innovation accompany good governance. The world has headed toward a low-carbon future where renewable energy systems, coming together in harmony with biodiversity conservation, will present a solid foundation for the establishment of a global ecosystem that is sustainable and resilient.

Deploying renewable energy and conserving biodiversity together can have a positive impact on the environment, the economy, and society, leading to a more resilient and sustainable future. Our energy needs will be satisfied while preserving the very ecosystems that sustain life on Earth if climate action and biodiversity protection are combined.

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Review

Integrating sustainability into project management for eco-friendly outcomes

Segun Kehinde

Department of Business Management, Covenant University, Ota 112104, Ogun State, Nigeria; segun.kehindepgs@stu.cu.edu.ng

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Abstract: The pursuit of sustainable project management practices is becoming increasingly important in contemporary project management discourse. This review explores the integration of sustainability principles and environmental considerations within project management frameworks, aiming to identify specific strategies that lead to eco-friendly project outcomes and foster long-term sustainability. By examining a broad range of scholarly works, empirical studies, and industry reports, this review highlights key methodologies for embedding environmental consciousness into project planning, execution, and evaluation. The findings reveal that incorporating sustainability principles into project management not only enhances project outcomes but also significantly reduces adverse environmental impacts. Specifically, the review identifies effective approaches such as life cycle assessment (LCA) and stakeholder engagement, which are shown to be instrumental in promoting sustainable practices across different project stages. Moreover, the study sheds light on common challenges, such as resistance to change and the lack of standardized sustainability metrics, and offers actionable recommendations for overcoming these barriers. In addition, the review discusses opportunities for advancing sustainable project management through the application of emerging technologies and cross-disciplinary collaboration. Insights from behavioral studies, environmental sciences, and management theories provide a comprehensive understanding of the factors driving the successful adoption of sustainability practices among project stakeholders. Ultimately, this review consolidates theoretical perspectives and empirical evidence to present a clear and detailed understanding of how sustainable project management practices can be effectively implemented to achieve environmentally responsible and enduring project outcomes.

Keywords: sustainable project management; environmental considerations; eco-friendly outcomes; long-term sustainability

1. Introduction

In recent years, the global discourse on project management has undergone a profound shift, placing an unprecedented emphasis on sustainability and environmental consciousness. The escalating concerns surrounding climate change, resource depletion, and environmental degradation have propelled the integration of sustainability principles into various domains, and notably, into the core of project management practices [1]. This paradigm shift necessitates a reevaluation of traditional project management frameworks, prompting an exploration into the seamless integration of sustainability principles and environmental considerations within project methodologies.

In an ideal world, project management practices seamlessly integrate sustainability principles and environmental considerations at their core, ensuring that every project undertaken prioritizes eco-friendly outcomes and long-term environmental sustainability. In this ideal scenario, project managers are equipped with comprehensive frameworks that effortlessly incorporate sustainability metrics, ethical sourcing, waste reduction strategies, and carbon footprint mitigation into every phase of project planning, execution, and evaluation. The seamless integration of sustainability within project management is reflected not merely as an option but as a fundamental criterion driving project success, fostering a paradigm where environmental consciousness is inherently entwined with project goals. However, the prevailing reality presents a stark contrast to this ideal scenario [2]. Globally, project management frameworks often overlook sustainability considerations, focusing predominantly on immediate project deliverables and economic objectives while sidelining ecological impacts. The problem extends to a lack of standardized guidelines and implementation frameworks that specifically address the integration of sustainability principles into project management practices. Locally, within specific industries or regions, the gap widens as limited awareness, insufficient resources, and a dearth of established protocols exacerbate the challenge of incorporating sustainability within project management. This disparity not only hampers the ability to address pressing environmental issues but also perpetuates an unsustainable approach to project execution. The consequences of failing to rectify this discrepancy between the ideal and the existing state are dire [3]. Without proactive measures to integrate sustainability into project management practices, the world faces heightened environmental degradation, escalating resource depletion, and increased carbon emissions attributable to project undertakings. The absence of standardized sustainability frameworks within project management not only undermines ecological preservation but also jeopardizes long-term socio-economic stability. Failure to address this gap could lead to perpetuating unsustainable practices, hindering global efforts toward achieving environmental sustainability goals, and exacerbating the adverse impacts of projects on the environment. Ultimately, the perpetuation of this disparity risks further degradation of natural ecosystems, impeding progress towards a more sustainable and resilient future for generations to come.

2. Literature review

In the realm of contemporary project management, a fundamental transformation is underway, marked by an increasing recognition of the imperative to embed sustainability principles into project frameworks. Several Studies underscore the significance of integrating sustainability metrics, ethical sourcing, waste reduction strategies, and carbon footprint mitigation into project planning, execution, and evaluation phases. The contemporary global landscape is witnessing a transformative shift in project management ideologies, where sustainability has emerged as a pivotal concern [4]. This shift signifies an evolution in societal values, reflecting an increasing awareness of environmental issues and the recognition of the imperative to address them within project management practices. The integration of sustainability principles into project frameworks signifies a departure from traditional project goals focused solely on economic viability towards a more holistic approach that incorporates environmental and social impacts. This paradigm shift aims to align project objectives with broader sustainability goals, emphasizing eco-friendly outcomes and long-term environmental preservation. Amid this paradigm shift lies the crucial need to assess the efficacy of integrating sustainability principles and environmental considerations into existing project management frameworks.

2.1. Historical evolution of sustainable project management

The historical evolution of sustainable project management traces a compelling journey that intertwines societal shifts, environmental awareness, and evolving project paradigms. Historically, project management focused primarily on efficiency, cost-effectiveness, and meeting deliverables within set timelines. Sustainability was not a focal point as projects were evaluated based on immediate gains without considering long-term environmental implications. The 20th century witnessed the awakening of environmental concerns globally. Events such as the publication of Rachel Carson's "Silent Spring" and the establishment of Earth Day in 1970 marked pivotal moments in raising awareness about environmental degradation [5]. This burgeoning consciousness catalyzed a shift in societal values, prompting a reevaluation of industrial practices, including project management. The late 20th and early 21st centuries marked a pivotal era for sustainable project management. Organizations began recognizing the significance of integrating sustainability principles into project frameworks. This involved considering ecological footprints, social responsibility, and economic viability in project planning, execution, and evaluation. International frameworks like the Global Reporting Initiative (GRI), Leadership in Energy and Environmental Design (LEED), and the Project Management Institute's (PMI) incorporation of sustainability into project management standards solidified the integration of sustainable practices. Certifications such as LEED accreditation and PMI's Project Management Professional (PMP) with an emphasis on sustainability further validated this shift [6]. International initiatives like the United Nations Sustainable Development Goals (SDGs) played a pivotal role in shaping project management practices. They provided a comprehensive roadmap, urging organizations to align projects with broader global sustainability objectives, influencing decision-making and project planning worldwide. Presently, sustainable project management stands as an indispensable aspect of modern project planning. It encompasses life cycle assessments, stakeholder engagement, risk mitigation for environmental impact, and the utilization of green technologies [7]. Looking ahead, the future of sustainable project management seems poised for further evolution, with an increasing focus on circular economy principles, carbon neutrality, and innovative technologies to enhance eco-friendly project outcomes.

Incorporating sustainability principles into project management frameworks leads to enhanced project outcomes, both in terms of performance and environmental impact. Using life cycle assessments (LCA) and engaging stakeholders early and often results in projects that not only meet their objectives but also contribute positively to the environment. For instance, LCA provides a holistic view of the environmental impact of a project from inception to completion, enabling project managers to make informed decisions that reduce resource consumption and waste. One of the significant gaps identified in current times is the lack of standardized sustainability metrics. Without a common framework for measuring sustainability, it is challenging to evaluate the effectiveness of sustainable practices across different projects and industries. The development of standardized metrics is crucial for ensuring that sustainability goals are met consistently [8]. These metrics should cover various aspects of sustainability, including energy efficiency, waste reduction, and social impact. Successful sustainable project management hinges on effective stakeholder engagement. Early and ongoing communication with stakeholders, including clients, suppliers, and the community, is crucial for aligning project goals with sustainability objectives. Engaging stakeholders in the decision-making process fosters a sense of ownership and encourages the adoption of eco-friendly practices. For instance, involving suppliers in discussions about sustainable sourcing can lead to more environmentally conscious procurement decisions. By integrating these practices and standardized metrics, projects can achieve their goals, better assess performance and make data-driven decisions while minimizing their ecological footprint, leading to a win-win scenario for both the business and the planet [9]. The chart below shows that 70% of companies have adopted sustainable project management practices, while 30% have not. This indicates a strong trend towards integrating sustainability in project management to achieve eco-friendly outcomes and long-term sustainability. **Figure 1** presents the Adoption of sustainable project management practices

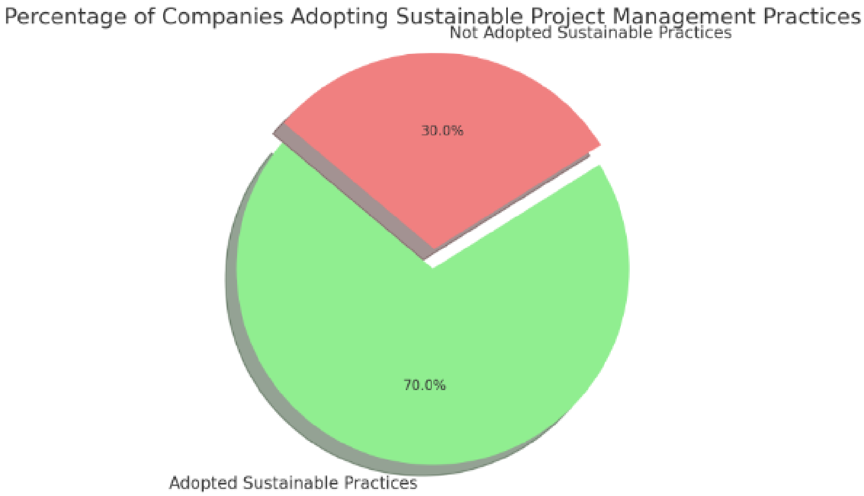

Figure 1. Adoption of sustainable project management practices.

Figure 2 presents Key sustainable project management practices implemented. This bar chart above highlights key sustainable project management practices implemented by companies. The practices include green procurement (80%), energy-efficient technologies (75%), waste reduction strategies (60%), and stakeholder engagement (50%). These practices are crucial for minimizing environmental impact and promoting sustainability.

Figure 2. Key sustainable project management practices implemented.

2.2. Theoretical frameworks in sustainable project management

Theoretical frameworks in sustainable project management provide the conceptual structure and guiding principles that underpin the integration of sustainability into project practices. These frameworks offer a systematic approach to incorporating environmental, social, and economic considerations within project management methodologies. Here are some key theoretical frameworks shaping sustainable project management:

1) Triple Bottom Line (TBL) Approach: The TBL framework, popularized by John Elkington, advocates for evaluating project success based on three interconnected pillars: social, environmental, and economic performance. It emphasizes the importance of not only financial outcomes (profit) but also societal impact (people) and environmental stewardship (planet) in project decision-making [10].
2) Life Cycle Assessment (LCA): LCA is a comprehensive methodology used to assess the environmental impacts of a product, process, or service throughout its entire life cycle. In sustainable project management, LCA helps in identifying and mitigating environmental hotspots, guiding decisions towards eco-friendly materials, efficient resource use, and waste reduction across all project stages.
3) Systems Thinking: Systems thinking involves viewing a project as an interconnected system of components where changes in one area can affect the entire system. In sustainable project management, this framework aids in understanding the complex relationships between project elements, stakeholders, and the environment, fostering holistic decision-making to achieve sustainable outcomes.
4) Corporate Social Responsibility (CSR): CSR frameworks emphasize an organization’s responsibility to operate ethically and contribute positively to society. When applied to project management, CSR principles guide projects to consider social impacts, engage stakeholders, promote fair labor practices, and contribute to community development alongside meeting project objectives.
5) Green Project Management (GPM): GPM focuses on integrating environmentally friendly practices into project management processes. It involves strategies such

as selecting sustainable materials, minimizing waste, optimizing energy efficiency, and adhering to environmental regulations throughout project lifecycles.

6) Sustainable Development Goals (SDGs): The United Nations' 17 SDGs provide a global framework for sustainable development, influencing project management practices. Aligning projects with SDGs allows for a broader perspective, enabling projects to contribute directly to global sustainability objectives.
7) Stakeholder Theory: Stakeholder theory emphasizes the importance of considering the interests of all stakeholders affected by a project. In sustainable project management, this framework emphasizes engaging diverse stakeholders, including communities, governments, NGOs, and future generations, ensuring their perspectives and concerns are addressed.

2.3. Challenges in integrating sustainability

Integrating sustainability into project management practices presents a series of complex challenges that organizations must navigate to achieve successful implementation. These challenges stem from various sources and demand proactive strategies to overcome. One primary challenge lies in the intricate interconnectedness of sustainability considerations across environmental, social, and economic domains. Projects often interact with diverse stakeholders, regulations, and ecosystems, making it challenging to account for all variables and their interdependencies. A significant hurdle is the limited awareness or understanding of sustainability principles among project stakeholders, including team members, clients, and investors. This lack of comprehension can impede the integration of sustainable practices. Education and awareness initiatives are essential to foster a shared understanding of sustainability goals and their relevance to project success. Moreover, the integration of sustainable practices might initially incur higher costs or resource demands, posing a challenge in balancing sustainability objectives with budget limitations and resource availability. Resistance to change within organizational cultures or entrenched traditional project management methodologies can hinder the adoption of sustainable practices [11]. Overcoming this resistance requires strong leadership, effective communication, and demonstrating the tangible benefits of sustainability in projects. Measuring and evaluating the impact of sustainability initiatives on project outcomes is another significant challenge due to the lack of standardized metrics and methods. Quantifying environmental, social, and economic impacts accurately remains a hurdle in demonstrating the effectiveness of sustainable practices. Additionally, navigating complex and evolving regulatory frameworks related to sustainability while maintaining project objectives demands thorough knowledge and continuous adaptation. Sustainability initiatives often extend beyond organizational boundaries, requiring collaboration across supply chains and stakeholders [12]. However, coordinating diverse partners and suppliers to align their practices with sustainability goals can be challenging due to differing priorities and capabilities. Balancing competing priorities where sustainability objectives might conflict with other project goals or stakeholder interests is a persistent challenge in integrating sustainability into project management.

2.4. Key reasons for barriers to large-scale implementation of eco-management principles

The large-scale implementation of eco-management principles in project management faces several barriers. A primary challenge is the perceived high cost associated with sustainable practices. Many companies, particularly in developing economies, prioritize short-term financial gains over long-term sustainability, which often requires upfront investment in green technologies, sustainable materials, and training. According to the World Bank, the upfront cost barrier is especially pronounced in small and medium-sized enterprises (SMEs), which may lack the capital to invest in sustainable practices despite long-term benefits. Another significant barrier is the lack of awareness and understanding of sustainability principles among key stakeholders. This is compounded by the absence of standardized guidelines and metrics for measuring sustainability in projects, leading to inconsistent application across industries. A survey by McKinsey & Company found that 44% of companies cited the complexity of integrating sustainability into existing frameworks as a major obstacle to large-scale adoption. Finally, regulatory and policy environments often do not incentivize sustainable practices. In many regions, environmental regulations are either weak or poorly enforced, allowing companies to ignore sustainability with minimal repercussions. In contrast, countries with stringent regulations, such as those in the European Union, have seen better integration of eco-management principles due to the combination of legal requirements and government incentives. Addressing these barriers requires a multi-faceted approach. Governments must play a crucial role by creating and enforcing regulations that promote sustainability and protect workers' rights. This could include introducing carbon pricing, providing subsidies for green technologies, and enforcing fair labor practices [13]. At the corporate level, companies should move beyond mere compliance and integrate sustainability into their core business strategies. This involves setting clear sustainability goals, measuring progress through standardized metrics, and ensuring transparency in reporting. Collaboration between governments, businesses, and civil society is essential to creating an environment where sustainable practices are the norm rather than the exception.

2.5. Best practices and innovative approaches

Exploring successful case studies, methodologies, and innovative strategies in integrating sustainability principles into project management reveals a diverse array of best practices that have yielded remarkable outcomes. Several case studies highlight exemplary instances where sustainability was seamlessly integrated into project management. For instance, the construction industry has seen projects achieve LEED (Leadership in Energy and Environmental Design) certification by employing eco-friendly materials, energy-efficient designs, and waste reduction strategies. These projects not only met environmental standards but also demonstrated cost-effectiveness and enhanced marketability. Certain methodologies have proven effective in embedding sustainability within project management frameworks.

Adopting Life Cycle Assessment (LCA) methodologies allowed organizations to comprehensively assess and mitigate environmental impacts across a project's lifecycle. Similarly, Triple Bottom Line (TBL) approaches ensured a balanced consideration of social, environmental, and economic aspects, guiding decisions toward sustainable outcomes. Innovation has played a pivotal role in fostering sustainability within project management. The use of advanced technologies like Building Information Modeling (BIM) facilitated efficient resource management, reduced material wastage, and enhanced collaboration among project stakeholders [14]. Additionally, agile project management methodologies have been adapted to incorporate sustainability iterations, enabling continuous improvement and adaptation to evolving sustainability goals. The successful integration of sustainability principles often hinges on effective stakeholder engagement. Projects that actively involved diverse stakeholders, including communities, governmental bodies, NGOs, and local residents, demonstrated a higher degree of acceptance, collaboration, and commitment to sustainable project outcomes. Adopting holistic approaches that consider the interconnectedness of sustainability elements throughout the project lifecycle has also proven highly effective. Incorporating circular economy principles, where materials are reused or repurposed, minimizes waste and contributes to a sustainable project ethos beyond project completion. Organizations that invested in educating and building the capacity of their workforce on sustainability principles witnessed smoother integration. Training programs, workshops, and certifications focused on sustainability empowered project teams to implement best practices effectively. Additionally, successful projects often tailored sustainability approaches to fit local contexts while aligning with global sustainability goals, such as the United Nations' Sustainable Development Goals (SDGs) [15]. Projects that embraced these goals not only contributed to global initiatives but also gained recognition for their commitment to broader sustainability objectives.

2.6. Considerations in project lifecycle

Understanding the influence of sustainability considerations across the project lifecycle, from initiation to closure, illuminates the pivotal role these factors play in shaping environmentally responsible outcomes.

Initiation Phase: During the project initiation phase, laying the groundwork for sustainability sets the tone for the entire project. Here, key decisions are made regarding project objectives, scope, and feasibility. Incorporating sustainability principles at this stage involves conducting environmental impact assessments, identifying potential risks to ecosystems or communities, and setting clear sustainability goals aligned with project objectives.

Planning and Design Phase: In the planning and design phase, the integration of sustainability principles takes center stage. This phase involves choosing materials, technologies, and methodologies that minimize environmental impact while maximizing efficiency. Concepts like Life Cycle Assessment (LCA) come into play, guiding decisions on resource usage, energy efficiency, waste reduction, and selecting eco-friendly materials [16]. Design considerations aim to optimize environmental performance without compromising project goals.

Execution Phase: As the project moves into the execution phase, translating sustainability plans into action becomes crucial. Implementing environmental management systems, adhering to environmental regulations, and monitoring key performance indicators related to sustainability help ensure that the project aligns with its environmental objectives. Collaboration with stakeholders, including suppliers and contractors, plays a critical role in ensuring that sustainability practices are effectively executed on the ground.

Monitoring and Control Phase: The monitoring and control phase involves ongoing assessment and adjustment of sustainability initiatives. Continuous monitoring of environmental impacts, tracking resource usage, and assessing compliance with sustainability benchmarks allow for timely intervention and corrective actions. Regular audits and performance reviews help in identifying areas for improvement and maintaining alignment with sustainability goals.

Closure and Post-Project Phase: As the project reaches closure, focusing on environmentally responsible closure practices is essential. Proper disposal of materials, site restoration, and transitioning to sustainable post-project operations are integral. This phase also involves evaluating the project's overall environmental performance, documenting lessons learned, and disseminating best practices for future projects.

2.7. Stakeholder engagement and impact assessment

The role of stakeholder engagement in sustainability integration within projects and the methods employed to assess its impact on stakeholders and project outcomes is crucial for ensuring alignment, transparency, and positive impacts. Stakeholder engagement is a cornerstone in the successful integration of sustainability into projects [17]. It involves identifying and involving diverse stakeholders, including communities, local authorities, NGOs, investors, and employees, throughout the project lifecycle. Their insights, concerns, and perspectives are essential in shaping sustainability strategies and decisions. Assessing the impact of sustainability integration on stakeholders requires robust methodologies. Surveys, interviews, focus groups, and workshops facilitate gathering stakeholders' perceptions, expectations, and concerns regarding sustainability initiatives. These methods aid in understanding stakeholders' attitudes towards sustainability, identifying their needs, and evaluating the effectiveness of engagement efforts. Analyzing the influence of stakeholder engagement on project outcomes involves assessing how their involvement affects decision-making, project design, and implementation. Key performance indicators (KPIs) related to stakeholder satisfaction, participation rates, changes in behavior or policies, and overall project success serve as benchmarks to measure stakeholder impact on project outcomes [18].

Tools such as Social Return on Investment (SROI), stakeholder mapping, and materiality assessments aid in comprehensively evaluating the impact of sustainability integration on stakeholders. SROI measures social, environmental, and economic outcomes to quantify the value created by stakeholder engagement. Stakeholder mapping identifies the significance and influence of different stakeholders on project decisions. Materiality assessments prioritize sustainability issues based on their significance to stakeholders and the project's objectives. Effective stakeholder engagement not only ensures that diverse perspectives are considered but also contributes to better decision-making, risk mitigation, and enhanced project credibility. It fosters trust, transparency, and accountability, ultimately leading to more sustainable and socially responsible project outcomes. Challenges in assessing stakeholder impact include the complexity of stakeholder dynamics, diverse interests, and the subjective nature of qualitative data. Balancing conflicting stakeholder interests and expectations while aligning them with project goals can also pose challenges.

The application of sustainable practices at the level of an individual enterprise is not only possible but also increasingly common across various sectors. For instance, in the agriculture sector, companies like Patagonia Provisions have implemented regenerative farming practices to restore soil health and reduce carbon emissions. Similarly, in the construction industry, firms are adopting green building standards like LEED to minimize environmental impact. While some argue that sustainability can only be achieved on a global scale, these examples demonstrate that individual enterprises can make significant contributions. However, the success of these initiatives often depends on the availability of resources, expertise, and supportive policy frameworks. To promote broader adoption, it is crucial to showcase successful case studies, provide incentives for sustainable practices, and offer guidance on integrating sustainability into business models.

2.8. Technology and tools for sustainable project management

Technological advancements and specialized tools play a pivotal role in enabling and enhancing sustainable project management practices, offering innovative solutions to address environmental, social, and economic considerations.

1) Data Analytics and Decision Support Systems: Advanced data analytics and decision support systems empower project managers to make informed decisions by analyzing vast amounts of data [19]. These tools assist in predicting environmental impacts, optimizing resource usage, and identifying opportunities for sustainability improvements throughout the project lifecycle.
2) Building Information Modeling (BIM): BIM is a technology that enables comprehensive digital representations of construction projects. It facilitates collaboration among stakeholders, improves design accuracy, and allows for efficient resource management. BIM’s visualization capabilities aid in assessing environmental impacts, optimizing energy efficiency, and reducing waste during the construction phase.
3) Internet of Things (IoT) and Sensor Technology: IoT devices and sensor technology offer real-time monitoring and data collection capabilities. They enable the tracking of environmental metrics like energy consumption, emissions, and resource utilization, allowing for immediate intervention to optimize sustainability performance.
4) Project Management Software with Sustainability Modules: Project management software equipped with specialized sustainability modules integrates sustainability considerations into project planning, execution, and reporting. These modules often include features for tracking carbon footprint, managing green certifications, and ensuring compliance with sustainability standards.

5) Life Cycle Assessment (LCA) Software: LCA software facilitates a comprehensive assessment of a project's environmental impacts across its entire life cycle. It helps in identifying hotspots, evaluating alternative materials or processes, and making informed decisions to minimize environmental footprints.
6) Remote Monitoring and Collaboration Tools: Remote monitoring tools and collaboration platforms enable geographically dispersed teams to work together seamlessly. These tools reduce the need for travel, thus lowering carbon emissions, while still fostering effective communication and collaboration among project stakeholders.
7) Blockchain for Transparency and Traceability: Blockchain technology ensures transparency and traceability in supply chains, allowing for the verification of sustainable sourcing practices, ethical labor, and adherence to environmental standards. It enhances trust among stakeholders by providing immutable records of sustainability-related transactions.
8) Virtual Reality (VR) and Augmented Reality (AR): VR and AR technologies aid in simulating and visualizing sustainable designs, enabling stakeholders to experience and assess the environmental impacts of different project scenarios. They facilitate better understanding and decision-making, especially in complex construction and infrastructure projects.

2.9. Regulatory frameworks and standards

The integration of sustainability principles into project management is significantly influenced by a myriad of global, regional, and industry-specific regulations, standards, and certifications. These frameworks serve as guiding principles and benchmarks for organizations aiming to align their projects with sustainability objectives.

Global Regulations and Initiatives: Global initiatives, such as the United Nations' Sustainable Development Goals (SDGs), provide a comprehensive framework for sustainable development. The 17 SDGs encompass diverse sustainability aspects, influencing project management practices worldwide by encouraging alignment with broader global sustainability objectives.

Regional Regulations and Policies: Various regions have their specific regulations and policies that influence project management. For instance, the European Union (EU) has directives focusing on environmental protection, energy efficiency, and waste management, impacting projects within member countries [20]. Regional bodies often set standards regarding emissions, resource usage, and sustainability reporting, affecting project planning and execution.

Industry-Specific Standards and Certifications: Industry-specific standards and certifications play a crucial role in shaping sustainability practices within sectors. For example, within the construction industry, Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) certifications set benchmarks for environmentally responsible building practices. Similarly, industries like manufacturing, energy, and agriculture have their set of standards guiding sustainable practices in their respective domains.

ISO Standards for Sustainability: The International Organization for Standardization (ISO) offers a range of standards relevant to sustainability in project management. ISO 14001 focuses on environmental management systems, ISO 26000 addresses social responsibility, and ISO 9001 outlines quality management systems—all of which intersect with project management and sustainability, influencing processes and practices.

Carbon Offsetting and Emissions Trading Schemes: Carbon offsetting mechanisms and emissions trading schemes, while not specific to project management, influence sustainability strategies. These frameworks incentivize or require organizations to offset their carbon emissions, influencing project decisions regarding energy usage, carbon reduction strategies, and investments in renewable energy projects.

Government Policies and Incentives: National governments often introduce policies and incentives to promote sustainable practices. Tax incentives, grants, and subsidies aimed at encouraging sustainable projects can significantly impact project planning and investment decisions.

Supply Chain and Procurement Standards: Standards and certifications related to supply chain and procurement practices, such as Fair Trade, Responsible Sourcing, or Forest Stewardship Council (FSC) certification, influence project material sourcing and supplier selection, ensuring adherence to sustainability criteria [21].

2.10. Social and ethical dimensions in sustainable projects

In sustainable project management, the social and ethical dimensions hold significant importance, encompassing various aspects that extend beyond environmental considerations. These dimensions involve fostering community engagement, addressing ethical considerations, and conducting social impact assessments to ensure holistic and responsible project outcomes.

Community Engagement: Engaging with local communities affected by projects is fundamental in sustainable project management. Meaningful engagement involves active participation, collaboration, and dialogue with stakeholders to understand their needs, concerns, and aspirations [22]. It enables projects to align with community interests, mitigate potential social disruptions, and foster a sense of ownership and support.

Ethical Considerations: Ethical considerations encompass a range of aspects, including fair labor practices, human rights, transparency, and integrity in project execution. Upholding ethical standards ensures that projects respect the dignity, rights, and well-being of individuals involved, including workers, stakeholders, and affected communities.

Social Impact Assessments: Conducting social impact assessments evaluates the potential positive and negative social effects of projects [23]. It involves identifying, predicting, and mitigating social risks or adverse impacts on communities, cultures, employment, and social infrastructure. These assessments inform decision-making processes and guide strategies to maximize positive social outcomes.

Inclusivity and Diversity: Promoting inclusivity and diversity within project teams and stakeholder engagement efforts is crucial. Embracing diverse perspectives, cultures, and backgrounds not only enriches project outcomes but also ensures equitable participation and representation of all stakeholders [24].

Respect for Cultural Heritage and Traditions: Projects must respect cultural heritage, traditions, and local knowledge systems. Respecting and preserving cultural values, historic sites, and indigenous knowledge contribute to maintaining social harmony and honoring the identity of affected communities.

Labor and Human Rights Compliance: Ensuring adherence to labor standards and human rights principles within project activities is paramount. This includes fair wages, safe working conditions, and respecting workers' rights, contributing to social well-being and sustainability.

Sustainable Livelihoods and Community Development: Sustainable projects aim to enhance local economies and promote community development. Creating opportunities for skill development, employment, and capacity building fosters sustainable livelihoods, empowering communities for long-term prosperity.

Social Responsibility and Accountability: Promoting social responsibility and accountability involves transparent communication, reporting on social impacts, and taking responsibility for any adverse effects caused by the project. It demonstrates commitment to addressing social concerns and learning from project experiences.

2.11. Economic implications of sustainability integration

Integrating sustainability principles into projects bears significant economic implications that extend beyond upfront costs. While initial investments may seem higher, the long-term economic benefits often outweigh these expenses.

Cost-Effectiveness in the Long Run: Sustainability integration emphasizes resource efficiency, reducing waste, and optimizing energy consumption [25]. While these measures may involve higher initial costs, they lead to long-term savings through reduced operational expenses, lower energy bills, and minimized waste disposal costs.

Return on Investment (ROI): Investments in sustainability often yield favorable returns. Implementing energy-efficient technologies, adopting sustainable practices in supply chains, and enhancing product lifecycle management contribute to improved efficiency and competitiveness, resulting in a positive ROI over time.

Long-Term Financial Benefits: Sustainability initiatives can lead to enhanced brand reputation, increased market share, and improved customer loyalty [26] Companies demonstrating commitment to sustainability often attract environmentally conscious consumers, investors, and partners, translating into long-term financial gains.

2.12. Cross-industry insights

Drawing insights from various industries reveals common trends and successful strategies in implementing sustainable project management practices.

Construction and Real Estate: In the construction sector, adopting green building practices not only reduces environmental impact but also attracts tenants willing to pay premiums for sustainable spaces. Long-term savings on operational costs due to energy-efficient designs and reduced maintenance contribute significantly to economic gains.

Manufacturing and Supply Chain Management: Implementing sustainability measures in manufacturing processes results in reduced waste, optimized use of raw materials, and enhanced efficiency [27]. Companies investing in renewable energy sources and sustainable supply chain practices experience cost savings and resilience against resource price fluctuations.

Technology and Innovation: The technology sector leverages sustainability through innovations in energy-efficient products, responsible e-waste management, and data center optimization. Embracing circular economy principles by designing products for durability and recycling contributes to economic benefits while reducing environmental impact.

Hospitality and Tourism: In hospitality, eco-friendly initiatives like water and energy conservation not only reduce operating costs but also attract eco-conscious travelers, enhancing market competitiveness and profitability. Sustainable tourism practices preserve natural resources, supporting local economies in the long term.

Finance and Investment: Financial institutions increasingly consider Environmental, Social, and Governance (ESG) criteria in investment decisions. Companies adhering to strong ESG principles often attract investors seeking long-term sustainable returns, driving capital towards sustainable projects [28].

Retail and Consumer Goods: Sustainable packaging, ethical sourcing, and responsible production practices resonate with environmentally conscious consumers, driving sales and brand loyalty. Companies investing in sustainability initiatives witness increased market share and customer trust.

2.13. Educational and training initiatives

Educational programs, training initiatives, and capacity-building efforts are pivotal in preparing project managers with the skills and knowledge required for effective sustainable project management. These initiatives encompass various aspects aimed at fostering expertise in integrating sustainability principles into project planning, execution, and evaluation.

Academic Programs and Courses: Many universities offer specialized academic programs, courses, and degrees focused on sustainable project management. These programs cover topics such as environmental sustainability, social responsibility, green technologies, and ethical considerations in project management [29]. They equip students with theoretical knowledge and practical skills essential for implementing sustainability in projects.

Certifications and Professional Development Programs: Certifications, such as LEED accreditation, Project Management Professional (PMP) with a focus on sustainability, and ISO standards training, provide specialized knowledge and recognition of proficiency in sustainable project management practices. Professional development programs offer ongoing training, workshops, and seminars to keep project managers updated with the latest trends and best practices in sustainability.

In-House Training and Workshops: Organizations often conduct in-house training sessions and workshops tailored to their specific industry or project needs. These sessions focus on integrating sustainability into the company's project management methodologies, emphasizing practical applications and case studies relevant to their projects.

Online Learning Platforms and Resources: Online platforms offer a plethora of resources, including webinars, e-learning courses, articles, and videos dedicated to sustainable project management. These resources provide flexibility for self-paced learning, allowing project managers to access valuable insights and knowledge at their convenience.

Collaborative Learning and Knowledge Sharing: Encouraging collaboration and knowledge sharing among project managers through forums, networking events, and community platforms fosters an environment for exchanging best practices, lessons learned, and innovative approaches in sustainable project management.

Experiential Learning and Practical Applications: Hands-on experiences, internships, and real-life project simulations offer invaluable learning opportunities. Engaging in practical applications enables project managers to implement sustainability concepts, navigate challenges, and apply learned skills in real-world scenarios [30].

Soft Skills Development: In addition to technical expertise, developing soft skills such as communication, stakeholder engagement, leadership, and change management is essential. These skills are critical for effectively navigating the human aspects of sustainable project management, including stakeholder buy-in, collaboration, and effective communication of sustainability goals.

2.14. Risk management and resilience in sustainable projects

Risk management strategies in sustainable projects encompass identifying, assessing, and mitigating environmental risks and uncertainties. This involves conducting thorough environmental impact assessments, scenario planning for climate-related risks, and developing contingency plans to mitigate potential environmental disruptions [31]. Resilience-building focuses on enhancing a project’s ability to adapt and recover from environmental challenges. Strategies include diversifying resource inputs, incorporating flexibility in project designs, adopting sustainable practices that reduce vulnerability to environmental risks, and integrating adaptive management approaches. Implementing adaptive management practices involves continuously monitoring environmental factors, adjusting project strategies in response to changing conditions, and fostering learning and innovation. It allows projects to adapt to unforeseen environmental changes, ensuring ongoing sustainability amidst uncertainties. Engaging stakeholders in risk identification and management processes fosters collective understanding and proactive measures to address environmental risks. Involving diverse perspectives enables the identification of risks that might not be immediately apparent, ensuring comprehensive risk mitigation strategies.

2.15. Measurement and metrics for sustainability integration

Life Cycle Assessments (LCA): LCA methodologies quantify environmental impacts across a project’s life cycle, including resource use, emissions, and waste generation. These metrics help evaluate the environmental performance of projects and identify areas for improvement in sustainability practices [32].

Carbon Footprint and Emissions Reductions: Measuring carbon footprint and tracking emissions reductions serve as key indicators of environmental impact reduction. Metrics related to greenhouse gas emissions, energy efficiency improvements, and adoption of renewable energy sources quantify a project's contribution to mitigating climate change.

Social Impact Assessments: Social impact assessments gauge the project's effects on communities, stakeholders, and social well-being. Metrics encompass indicators like employment generation, community development, social equity, and stakeholder satisfaction, providing insights into the project's societal contributions.

Financial Performance and ROI: Evaluating financial performance through metrics like return on investment (ROI), cost savings from sustainable practices, and market competitiveness due to sustainability initiatives measures the economic impact of sustainability integration.

Compliance with Standards and Certifications: Adherence to industry standards, certifications (such as LEED, BREEAM), and regulatory compliance metrics demonstrates the project's commitment to meeting established sustainability benchmarks.

Stakeholder Perception and Engagement Metrics: Surveys, feedback mechanisms, and qualitative assessments capture stakeholder perceptions and engagement levels regarding sustainability initiatives. Metrics include measures of stakeholder satisfaction, trust, and involvement in project decision-making processes related to sustainability.

2.16. Cultural and behavioral aspects

The successful implementation of sustainable project management practices is deeply influenced by cultural dynamics, behavioral factors, and leadership styles within organizations. Understanding and leveraging these aspects are crucial for fostering a sustainable project management ethos.

Organizational Culture: The prevailing organizational culture significantly shapes the adoption of sustainable practices. Cultures that prioritize innovation, collaboration, transparency, and social responsibility tend to embrace sustainability more readily. An organizational culture that values long-term thinking and environmental stewardship fosters a conducive environment for sustainable project management.

Behavioral Factors: Individual behaviors and attitudes play a pivotal role in the adoption of sustainable practices. Employee engagement, commitment, and willingness to embrace change impact the success of sustainability initiatives [33]. Encouraging behaviors such as environmental consciousness, resourcefulness, and open communication facilitates the integration of sustainability into project management.

Leadership Influence: Leadership styles greatly influence the organizational approach toward sustainability. Transformational leaders who articulate a clear vision, champion sustainability, and lead by example inspire teams to embrace sustainable practices. Their commitment to sustainability fosters a culture where sustainability is seen as a core organizational value.

Employee Engagement and Empowerment: Empowering employees by involving them in decision-making processes related to sustainability initiatives fosters ownership and commitment. Engaged employees contribute innovative ideas, drive change, and advocate for sustainable practices within their teams, enhancing the overall success of sustainability integration.

Change Management Strategies: Effective change management strategies are essential for embedding sustainability into organizational norms. Addressing resistance to change, communicating the benefits of sustainability, providing training and support, and celebrating successes are critical components of successful change management [34].

Cross-Functional Collaboration: Promoting collaboration among diverse departments and stakeholders facilitates the integration of sustainability into project management. Breaking down silos and encouraging cross-functional teamwork enables the alignment of diverse perspectives and expertise towards sustainable project goals.

Long-Term Vision and Strategic Alignment: A long-term vision aligned with sustainability goals ensures that projects are not solely focused on short-term gains but also consider their broader impact. Strategic alignment of sustainability initiatives with organizational objectives creates a framework where sustainability becomes an inherent part of project planning and execution.

Incentives and Recognition: Rewarding and recognizing individuals or teams for contributions to sustainability fosters a culture that values and encourages sustainable practices. Incentives, such as performance bonuses tied to sustainability goals, motivate employees to actively participate in sustainable project management.

3. Theoretical framework

One potent theory that strongly supports the integration of sustainability into project management is the “Triple Bottom Line” (TBL) theory. The Triple Bottom Line theory, introduced by John Elkington in the 1990s, suggests that organizations should evaluate their performance not only based on economic gains (the traditional bottom line) but also on social and environmental factors. Elkington, a British author and entrepreneur, first coined the term in his book “Cannibals with Forks: The Triple Bottom Line of 21st Century Business [35]. It encompasses three dimensions: profit, people, and planet. The TBL theory proposes that sustainable business practices consider the economic, social, and environmental impacts of business decisions. The Triple Bottom Line theory aligns seamlessly with the essence of sustainable project management by broadening the scope of project success criteria beyond financial gains. It emphasizes the integration of sustainability principles and environmental considerations within project management frameworks. By incorporating the “people” and “planet” dimensions alongside the economic aspect, the theory advocates for project outcomes that prioritize not just profitability but also social well-being and environmental stewardship.

4. Future trends and recommendations

4.1. Future trends in sustainable project management

1) Technology Integration: Continued advancements in technology, including AI, IoT, and blockchain, will further revolutionize sustainable project management by enabling more accurate data collection, predictive analytics, and enhanced monitoring of sustainability metrics.
2) Circular Economy Adoption: Increasing focus on circular economy principles will reshape project designs, emphasizing resource efficiency, product lifecycle management, and waste reduction, thus minimizing environmental impact.
3) Climate Resilience: Projects will prioritize climate resilience strategies, incorporating adaptation measures to mitigate risks arising from climate change, such as extreme weather events and rising sea levels.
4) ESG Integration: Environmental, Social, and Governance (ESG) considerations will become integral in project financing and investment decisions, influencing project planning to align with ESG goals.
5) Multi-Stakeholder Collaboration: Enhanced collaboration among governments, industries, NGOs, and local communities will drive more inclusive and comprehensive approaches to sustainable project management.

4.2. Adherence to sustainable development by transnational companies in the context of globalization

Transnational companies (TNCs) operate across multiple countries, often with varying environmental and labor standards. In the context of globalization, these companies face pressure to adhere to the principles of sustainable development and respect for the environment and their personnel. However, the extent of their adherence varies significantly. Research shows that while many TNCs publicly commit to sustainability goals, their actual practices can be inconsistent. A report by the United Nations Conference on Trade and Development (UNCTAD) found that only 20% of the world's largest TNCs fully integrate sustainability into their core business strategies. The remaining 80% often engage in "greenwashing," where they promote environmentally friendly initiatives without substantial changes to their overall operations. Despite this, there are examples of TNCs that have successfully integrated sustainability into their global operations. For instance, Unilever has been recognized for its Sustainable Living Plan, which aims to decouple growth from environmental impact while increasing its positive social impact [36]. This includes adhering to strict environmental standards across all its global operations and promoting fair labor practices. The implementation of principles such as respect for workers' rights and fair wages by TNCs varies widely depending on the region and industry. In countries with strong labor laws, TNCs are often compelled to comply with these principles. However, in regions with weaker regulations, there is a significant gap between corporate commitments and actual practices. For instance, the apparel industry has faced scrutiny for labor practices in developing countries. According to the International Labour Organization (ILO), despite commitments to fair wages and safe working conditions, many factories supplying TNCs still operate under poor conditions. This highlights the need for stronger international frameworks and more rigorous enforcement of labor standards to ensure that TNCs respect workers' rights globally. The graph shown in **Figure 3**, shows a significant increase in the integration of sustainability principles in project management frameworks from 2010 to 2020, rising from 40% to 85%. This trend reflects a growing recognition of the importance of sustainability in achieving long-term project success. **Figure 3** presents the Trend of sustainability integration in project management (2010–2020).

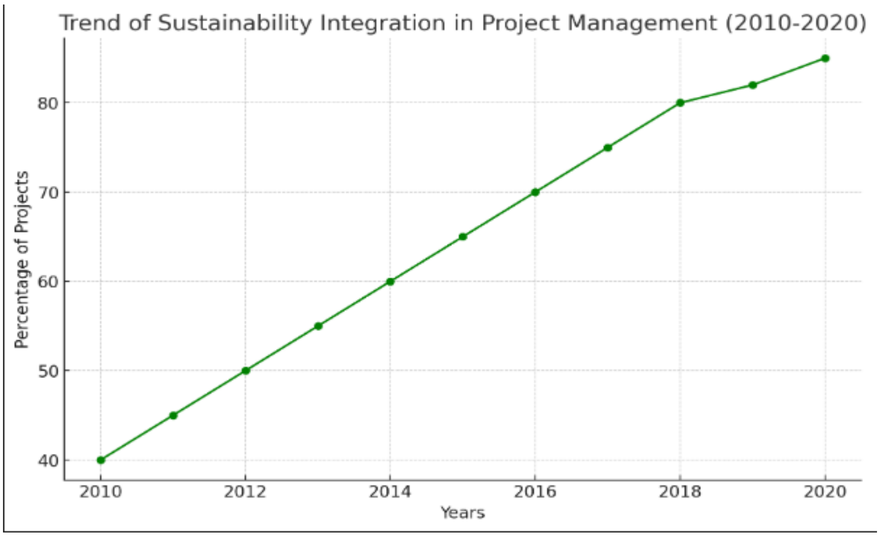

Figure 3. Trend of sustainability integration in project management (2010–2020).

Figure 4 presents the Environmental benefits of sustainable project management practices. This chart above displays the environmental benefits achieved through sustainable project management practices. These benefits include a 30% reduction in carbon emissions, a 25% decrease in water usage, a 20% reduction in waste generation, and a 15% improvement in biodiversity. These outcomes highlight the positive impact of integrating sustainability into project management.

Figure 4. Environmental benefits of sustainable project management practices.

4.3. Recommendations for refining sustainable project management

1) Continuous Education and Training: Invest in ongoing education and training programs to equip project managers with evolving sustainability skills and best practices.
2) Metrics Enhancement: Develop standardized and universally accepted metrics for measuring sustainability impact, enabling better benchmarking and comparison across projects and industries.
3) Holistic Integration: Encourage a holistic approach to sustainability integration by considering social, environmental, and economic aspects throughout the project lifecycle.
4) Regulatory Alignment: Advocate for regulatory frameworks that incentivize and support sustainable practices, fostering a conducive environment for sustainable project management.
5) Innovation and Collaboration: Foster a culture of innovation and collaboration within organizations to encourage experimentation with new sustainable technologies and methodologies.
6) Transparency and Reporting: Emphasize transparent reporting of sustainability efforts, ensuring accountability and enabling stakeholders to make informed decisions.
7) Stakeholder Engagement: Strengthen stakeholder engagement by involving diverse voices, ensuring their concerns and perspectives are integrated into project planning and execution.
8) Resilience Planning: Integrate resilience planning into project strategies, accounting for uncertainties posed by climate change and other disruptive factors.

4.4. Practical applicability

In the context of sustainable project management, the TBL theory guides project managers to assess project success based on a broader set of criteria. It prompts project teams to evaluate projects not only in terms of financial viability but also in terms of their social impacts on stakeholders and their environmental footprints [37]. This theory advocates for measuring and reporting social and environmental outcomes alongside economic performance. The TBL theory offers a structured approach for decision-making in project management. It encourages project managers to consider the potential impacts of projects on people (stakeholders, community) and the planet (environment) while pursuing profitability. By using this approach, project managers can identify opportunities to integrate sustainability principles, ethical considerations, and environmentally friendly practices into project frameworks, ultimately promoting eco-friendly project outcomes and ensuring long-term sustainability.

Moreover, the TBL theory promotes stakeholder engagement and accountability. It encourages project managers to involve diverse stakeholders, considering their social and environmental concerns. This inclusive approach fosters collaboration, transparency, and shared responsibility among stakeholders in driving projects toward more sustainable and eco-friendly outcomes. In summary, the Triple Bottom Line theory provides a robust foundation for integrating sustainability principles and environmental considerations into project management. It offers a framework that goes beyond financial metrics, emphasizing the importance of social and environmental impacts in project decision-making. By adopting this theory, project managers can effectively steer projects towards eco-friendly outcomes and long-term sustainability by balancing economic gains with social well-being and environmental preservation.

5. Conclusion

The exploration of sustainable project management practices signifies a transformative shift towards integrating sustainability principles and environmental considerations within project frameworks. This pursuit aims to transcend traditional project goals, prioritizing eco-friendly outcomes and long-term sustainability. The evaluation of these practices involves assessing the efficacy of embedding sustainability metrics, ethical sourcing, waste reduction strategies, and carbon footprint mitigation throughout project phases. Challenges emerge, including the lack of standardized guidelines and limited awareness, hindering seamless sustainability integration. Failure to bridge this gap threatens environmental stability and perpetuates unsustainable practices, emphasizing the urgency of cohesive sustainability integration in project management. This paradigm shift redefines project success, emphasizing a holistic approach that amalgamates economic viability with environmental preservation. The transformative potential of sustainable project management practices not only mitigates adverse environmental impacts but also fosters resilience within ecosystems. However, to attain enduring sustainability, concerted efforts are imperative to recalibrate project management methodologies towards eco-friendly outcomes.

The future of sustainable project management lies in leveraging emerging technologies and fostering cross-disciplinary collaboration. Digital tools, such as Building Information Modeling (BIM) and the Internet of Things (IoT), help in enhancing the efficiency and sustainability of projects. These technologies enable real-time monitoring and data-driven decision-making, which can significantly reduce waste and improve resource allocation. Moreover, collaboration between environmental scientists, behavioral experts, and project managers is essential for developing innovative strategies that drive sustainable practices. By breaking down silos and encouraging knowledge exchange, projects can be managed in a way that aligns with broader environmental goals while still delivering on time and within budget. The integration of sustainability principles within project management frameworks isn’t a mere choice; it’s an ethical imperative and a responsible commitment towards a sustainable future—a future where project success thrives in harmony with environmental preservation, leaving no room for debate.

Suggestions for further study

Suggestions for further study within the realm of sustainable project management practices open avenues for continuous exploration and advancement:

1) Impact Assessment Frameworks: Further research could focus on developing comprehensive impact assessment frameworks specific to sustainable project management. These frameworks would facilitate the quantification and

evaluation of environmental, social, and economic impacts arising from sustainable project practices, aiding in decision-making and reporting.

2) Technology Integration: Investigating the role of emerging technologies (e.g., AI, IoT, blockchain) in enhancing sustainability within project management offers promising research prospects. This exploration could focus on how these technologies facilitate eco-friendly practices, streamline processes, and optimize resource utilization.
3) Cross-Cultural Sustainability: Considering the global nature of projects, studying the implications of cultural diversity on sustainable project management is crucial. Research could assess how cultural differences influence sustainability perceptions, practices, and stakeholder engagement strategies across various regions.
4) Policy and Regulatory Impact: Exploring the influence of policies and regulations on sustainable project management practices is essential. Research could analyze how governmental policies, standards, and certifications shape the integration of sustainability principles into project frameworks.
5) Resilience and Adaptability: Given the dynamic nature of environmental challenges, researching resilience and adaptability within sustainable project management becomes imperative. This could involve studying strategies that enhance project resilience in the face of changing environmental conditions and unforeseen disruptions.

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Asia Pacific Academy of Science Pte. Ltd.

Add: 73 UPPER Paya Lebar Road #07-02B, Centro Bianco, Singapore 534818
Tel: +65 91384018
E-mail: editorial_office@apacsci.com
Web: https://aber.apacsci.com/