Journal of Environmental Science and Economics
https://doi.org/10.56556/jescae.v3i4.997
ISSN: 2832-6032

REVIEW ARTICLE

Sustainable Resource Management and Economic Development: Evaluating the Impact of Rare Earth Mining on Local Economies and Environmental Sustainability in China

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Received: 01 September, 2024, Accepted: 23 September, 2024, Published: 24 October, 2024

Abstract
Chinese mining is vital to the global economy due to its strategic supply of rare earth elements (REEs) necessary for the production of high-quality technologies such as wind turbines, electric vehicles, and many others. Through direct employment and sources of industries, China, which is a major producer in the global market, has revolutionized the local and national economy. However, similar to many other mining processes, this also creates critical problems of environmental pollution, destruction of habitat, and loss of biological diversity, which raises sustainability questions. The study review assembles prior literature on the economic effects and environmental costs of rare earth mining in China, assesses their sustainable management and suggests the areas for further research. The review covers both empirical papers and theoretical articles, as well as policy documents and environmental reports. This systematic cross-database search of the key terms resulted in the following finding: The implication drawn from the research is that, though the mining of rare earth is beneficial for development, it has negative impacts on the environment. Globally, sustainable management practices have elicited mixed success in managing the impacts of the concerns that arise, thus showing the need to adopt scale-appropriate solutions. However, due to the high level of heterogeneity that has been evidenced from the studies, more refined research and policies are required. For the purpose of furthering the sustainable goal in balance with the economic profit, future research should focus on the longitudinal setting and assess the performance of the sustainable practices within areas of rare earth mining in China.

Keywords: Rare earth mining; Economic impact; Environmental sustainability; Local economies; Sustainable resource management.

Introduction

China's REE mining is central to the world economy as the demand for REE in modern devices like high-performance magnets, green technologies, wind energy, hybrid vehicles, and warfare applications rises (Wu *et al.*, 2024). China has a massive influence over the rare earth industry because it possesses 60% – 70% of the market (Abbas *et al.*, 2024). This form of market control has great economic significance and can be represented through opportunities for employment, regional growth, and foreign exchanges. Similarly to minerals, rare earth elements have been gaining high value in technology and militarized industries, strengthening China's importance in the supply chain (Shuai *et al.*, 2023). However, the social and environmental implications of mining the rare earth in China have been stretched despite the merit that accrues. The environmental effects are soil and water pollution, emissions of gases, and reduction of bio-diversity, as Pradhan et al. 2024 pointed out concerning the extraction and processing of the required rare earth materials. Such processes result in the production of hazardous substances that persistently harm the environment and undermine sustainable development in the concerned areas (Zadokar *et al.*, 2023). However, polluting the environment to this level is a disadvantage that has grown the awareness of the global society on how sustainable mining could be. For instance, a review done by Pradhan et al. confirms that among the concerns raised is that extraction is presumed to use chemicals that affect the environment and are harmful to human health. The study also pointed out that the social impacts of mining rare earth in Global China mean they are also not free from adverse effects. Several mining areas are characterized by weak legal framework and implementation, which leads to unfavourable health conditions and social effects in the world's mining regions (Sager and Wiche, 2024). Several communities also mention displacement and loss of local livelihoods as the negative impacts of mining, mainly when mining is extensive (Li *et al.*, 2024). Lessons such as these social costs can make one appreciate that much debate is in progress as to whether rare earth mining is worth or profitable since, while net benefits are mostly reckoned in terms of profit, costs are reckoned in terms of loss to human and environmental lives. Considering the increasing use of rare earth elements and the associated environmental safety and responsibility issues, it is crucial to reform rare earth mining practices. The academic literature underscores the importance of balancing economic profits with environmental and social responsibility (Diogo *et al.*, 2022). Incorporating immersive technology in extraction methods, strengthening regulatory standards, and fostering global partnerships are vital strategies to mitigate the detrimental effects of rare earth mining while ensuring a steady supply of these metals (Jowitt, 2022). If the global trend towards environmentally sound technologies and sustainable development goals is any indication, the rare earth mining industry has the potential to transform and thrive in the future. Ultimately, the prospect of mining rare earth elements in China is a highly polarized issue, with significant benefits often balanced against extensive negative implications for the environment and social well-being (Liu *et al.*, 2023). In light of these, this paper aims to establish a safer and more sustainable mining method for REEs as the world's demand for the element increases. Policymakers, industries, and academics must recognize the challenges associated with mining these rare elements and take proactive steps to shape the future of this industry. Their collective efforts can lead to the formulation of policies that promote sustainable mining practices and ensure the long-term viability of the rare earth industry. Therefore, this review paper aims to synthesize prior literature on the economic and ecological effects of mining rare earths in China. These include the assessment of the impact that such activities have on local economic boost and the physical environment, examination of the literature to determine the identified or possible sustainable management practices that have been put forward and or can be, and finally, the revelation of critical research area missing in the current knowledge base. Such a review of the existing literature is presented here to guide further research and policy formulation for the sustainable mining of rare earths for economic growth without compromising the environment, emphasizing the urgent need for sustainable management practices.

Review of Literature

Economic Impacts

Similar to other human activities, the research on the economic effects of rare earth mining on the Chinese economy has its strengths and weaknesses. Notably, mining for rare earth has significantly boosted the economies of specific

Chinese provinces, such as Inner Mongolia and Jiangxi province, demonstrating the regional impact of the industry. As highlighted by (Kamenopoulos and Agioutantis, 2013), the mining of rare earth has led to the provision of employment opportunities and improved business circles. This has enhanced the sector's infrastructure and increased local government taxes and royalties. Investment and resource availability means that some areas gain more than others. (Mancheri *et al.*, 2019) analysed China's strategic dominance in the rare earth market and its national economic implications. Rare earth manufacturing allows China to use these resources for economic expansion and geopolitical power. Exports boost the economy by supporting technology, defence, and renewable energy. (Mejame *et al.*, 2022) found that sustainable rare earth mining practices reduce environmental damage and boost long-term economic stability. Sustainable mining can lower environmental cleanup costs and boost the industry's reputation, improving economic outcomes. Rare earth mining employment and income implications in mining localities have been thoroughly examined. (Palle Paul Mejame *et al.*, 2022) discovered that rare earth mining has created many jobs in the mining sector and adjacent businesses like transportation, equipment manufacture, and services. Job creation has raised incomes in some locations, improving local living standards. Mining's socioeconomic effects, according to (Abbas *et al.*, 2024), have increased employment but varied in quality and stability. Workers in low-skilled, transitory mining occupations have little economic security. Workers in mining locations may boost housing and service demand, raising living prices and negating wage increases. (Dou, Xu and Keenan, 2023) advised mining regions to diversify their economies to avoid overdependence on mining. Rare earth mining offers vital jobs, but regions that rely heavily on it may face economic issues if market conditions shift or resources dwindle. Promoting alternative businesses can stabilise employment and income in these communities.

Rare earth mining in China has economic benefits but also concerns that could threaten economic stability. (Wang *et al.*, 2022) noted rare earth market instability. Demand for rare earth elements in the international market, as well as policies and regulations of exporting countries and geopolitical factors, make the price of these elements fluctuate globally. It can be a disadvantage to mining businesses as well as to the regions as it causes fluctuations in revenue. (Jouini *et al.*, 2022) have briefly described a few effects of the mining of rare earth on some places economically. Such communities are at the mercy of the rollercoaster cycles of the extractive industry. Because of dependency, when the mining sector slows down, it leads to unemployment and a decrease in the revenue collected by the local government. Using data from (Zhang *et al.*, 2024), it is evident that mining of rare earth results in economic disparities. It indicated that some places benefit from economic mining, but other places suffer because of the unequal distribution of natural resources and investments. They might cause social tensions and disparities in access to and use of resources, which, in turn, perpetuates regional inequity. (Zhao *et al.*, 2019) pointed out that rare earth mining brings about other problems both for the environment and for the economy. They argued that as much as mining pushes the economy forward, environmental degradation affects residents and the economy negatively in the long run. Such problems require policies that promote economic development and growth while at the same time preserving the environment. Despite numerous challenges, rare earth mining in China impacts the people and economy of China. Employment and income growth are advantages, but market instability, dependency on economic growth, and environmental pollution are disadvantages. Several studies have analyzed the fact that increasing sustainable practices and diversifying the mining region’s economy will help to make positive changes in the region and decrease the negative impact of rare earth mining.

Environmental Impacts

This study's findings indicate that rare earth mining poses high risks to the environment and has negative impacts in areas where mining is intensive. Mining and refining rare earth elements result in the formation of hazardous byproducts, including heavy metals, which affect the environment. The mining of rare earth releases a cocktail of toxic metals into the soil and water, including lead, cadmium, and arsenic, along with radioactive materials such as thorium and uranium. These toxins have the potential to severely pollute water bodies, thereby affecting aquatic life and humans (Baz *et al.*, 2022). It is also emphasized that water pollution could have a significant impact on agriculture and drinking water, leading to the degradation of the environment. It is crucial to note that mining of rare earths is known to contaminate the air as well. The process might involve the use of dangerous dust, which is effectively extracted and processed. Mining airborne pollutants can cause respiratory and other challenges in neighboring communities (Yu and Zahidi, 2023). The study also found that rare earth mining air pollution can precipitate acid rain and damage the soil and water. Mining of rare earths utilities the ecosystem and decreases bio-diversity. Mining habitat destruction displaces species and destabilizes ecosystems. Loss of bio-diversity weakens the ecosystem's capacity to rebound aftershocks; hence, these habitats are easily degraded (da Silva-Rêgo, de Almeida and Gasparotto, 2022).

The issue of rare earth mining is further compounded by the long-term nature of the damage it causes. The presence of numerous toxins, coupled with their significant impacts on ecosystems, makes the rehabilitation of areas affected by rare earth mining a daunting task. It is worth noting that the mining of rare earth leads to the long-term pollution of the soil and water (Drusche and Kretschmann, 2023). Even after mining has ceased, pollutants continue to seep into the environment, perpetuating harm to ecology. The steady and constant decline in soil fertility and water quality lowers the productivity of farmland, and hence food production in the affected countries. The attempt to remediate rare earth mining environmental areas has had some rates of success (Xie *et al.*, 2020). The applications of both soil washing and phytoremediation to deal with contamination of mining sites. These technologies reduce pollution levels, but are capital intensive and require constant maintenance. The research established that the site pollution and the environmental conditions impair the cleanup exercise efficiency. Mining for rare earth affects the ecosystem of soil and water for any region and it is long term damage (Yin *et al.*, 2021). It is indicated that change in ecosystem dynamics of the communities is occasioned by mining-induced loss of biological diversity as well as habitat destruction. These changes can last decades, always negative impact on the species and the communities, which are dependent on the ecosystems. The identified study revealed that ecosystem recovery entails the acceptance, utilization and implementation of effective environmental management strategies (Bielawski, 2020). Although the operation of mining rare earth is slightly different from that of other mining and resource extraction, it also poses special environmental concerns as well as other similar industries. The mining of rare earth is similar to any mining in that it displaces wildlife and degrades soil and water. From the numerous works available to read, it was evident that (Liu *et al.*, 2021) explored the impact of mining on land and the environmental degradation that occurs and in their work, they pointed out that mining such as rare earth mining, coal and metal mining drastically affect land and pollute it. These contaminants and their chronic effects differ in countries, mining methods, and different kinds. As a result of this, it can be noted that, unlike mining of other minerals, rare earth mining has specific environmental implications as a result of the radioactive parts of the ores. (Klinger, 2023) stated that, unlike other mining, rare earth mining and processing present lasting hazards to the environment and human health. This issue needs specialised waste management to maintain the environment and the health of the population. Distinct techniques employed in the extraction of resources have distinct measures of containing the impacts on the external environment. Specifically, (Chen and Zheng, 2019) paid attention to Chinese rare earth mining's measures for environmental protection, such as improved management of waste and more legislation. These efforts are similar to reforestation as well as the treatment processes of water in many other mining industries to assess their effectiveness and applicability. The mining of rare earth leads to contamination, environmental destruction, and long-term disruption of natural habitats. While some of these effects can be mitigated through remediation, the unique characteristics of rare earth mining, such as radiation management and biodiversity, require constant and targeted efforts. Studies on other mining types reveal both common and specific environmental concerns, highlighting the need for ongoing and comprehensive environmental planning in the mining industry.

Sustainable Management Practices

For environmental and resource sustainability reasons, the mining of rare earths in China is now under a sustainable management system. To this end, the Chinese government has integrally addressed the issue of responsible mining from industry players. China's regulations for the mining of rare earth are strict when it comes to environmental standards. (da Silveira Pereira *et al.*, 2023) proposed issues relating to environmental standards such as EIA and limitation of mining chemicals. These policies also set aside sanctuaries to preserve species and cushion the effects of mining on ecosystems. Other legal requirements regarding the industry have also encouraged sustainable mining practices among players within the industry. According to the work of (Li, Li and Pan, 2024), most Chinese mining companies have also embraced international standards such as ISO 14001 in their operations. Such standards help firms to coordinate their environmental obligations better and thus minimize their impact on the environment. China also employs combined processes to optimize the utilization of REEs and to reduce the amounts wasted. Lee and Wen, 2018 presented the idea of recycling garbage and recovery byproducts in order to raise resource productivity and decrease the negative effects on the environment. The following techniques enhance China's circular economy and the country's industrial environmental objectives. China is poised to potentially revolutionize its rare earth mining practices to align with global standards, a move that could significantly enhance the industry's sustainability. This shift could see China adopting stringent environmental policies similar to those in Australia, a country known for its robust mining regulations. (Mehennaoui *et al.*, 2024) evaluated Australia's mine closure and land rehabilitation policy, which restores mining sites to their natural state or repurposes them. This thorough mine closure technique could be a model for China, where poor closure practices have caused long-term environmental damage. Mining sustainability in Canada emphasises community engagement and environmental management. (He *et al.*, 2021) demonstrated how Canadian mining firms work with local communities and indigenous organisations to construct sustainable projects. This collaborative method builds trust and improves community socio-economic well-being, which China may improve to ensure mining activities benefit local development. Chile's mining sector has improved sustainable water management, a major challenge in arid regions. Zhang et al. (2023) noted that Chilean mining corporations use water recycling and desalination to conserve freshwater. Consequently, water scarcity has the potential to worsen environmental effects in Chinese rare earth mining areas, making these practices necessary. Similar methods could reduce mining's impact on the environment and enhance water security. Information opportunities enable an organisation to lessen mining's effects on the environment and enhance its benefits. These include development in areas of using modern techniques in mining as well as developing and implementing proper instruments for achieving increased mining sustainability. These methods help minimise mining wastes and the emission of poisonous gases into the environment. Thus, (Pan, 2023) analysed that sophisticated separation techniques applied for rare earth metals ores decrease the usage of chemicals and enhance mineral recovery. They are effective in minimising pollution to the environment as well as increasing yields, thus making mining more economically viable. The mining industry has expanded the efficiency and effectiveness of mining processes and practices through technology and automation. As pointed out by Mejame et al. (2022), automation leads to low consumption of energy, increased safety of the workers, and efficiency in the utilisation of resources. Mine monitoring is boosted through the use of remote sensing and analytics, which in turn enhance sustainability. There is increasing use of recycling and circular economy options for sustainable mining. (Tian *et al.*, 2020) called for the recycling of REE from e-trash as well as industrial scrap to minimize the effects of mining and the use of virgin raw materials. It suggests that by lessening the social costs of mining, these strategies could assist China in transforming its economy towards being far more sustainable and differentiated.

Methodology

In order to implement a thorough literature review on "Sustainable Resource Management and Economic Development: In the methodological decision to implement the research, titled "Evaluating the Impact of Rare Earth Mining on Local Economies and Environmental Sustainability in China," systematization of the literature search was employed. The aim was to systematically look for, appraise, and integrate relevant studies on the economic and environmental costs of REE mining in China. The search was performed in several databases and search engines such as Scopus, JSTOR, Web of Science, Google Scholar, and PubMed. Each of them was selected for their unique features in indexing articles in various fields such as economics, environment and sustainable development. Based on the search results, the specific key terms used in the research were 'rare earth mining', 'economic benefit', 'environmental cost', 'China', 'local economy', 'sustainable mining', 'environmental impact assessment' and 'socioeconomic consequences'. Since the aim was to search selectively for studies that directly compare the impacts of rare earth mining on both economic growth and ecological health in China, Boolean operators were used to combine these terms. The literature review on "Sustainable Resource Management and Economic Development: Different Study Types was used to gather enough information and comprehend the gist of the topic in the article "Evaluating the Impact of Rare Earth Mining on Local Economies and Environmental Sustainability in China". The review also incorporated empirical works that presented the quantitative and qualitative results of the economic and environmental impacts of rare earth mining to ensure that the impacts on the local economy and sustainability were assessed based on available findings. However, theoretical papers were included to provide conceptualizations of the general underlying theories of the study in relation to the conservation and management of rare earth minerals. Additionally, policy comparisons were performed to assess the effectiveness of current laws and processes that address the extraction of rare earth in China to understand policy improvements. Environmental audits evaluated softer aspects of the effects of mining on ecological balance, like pollution levels, disruption of habitats, and long-term sustainability. The angles chosen in the review aimed at giving a broad perspective concerning the various impacts of rare earth mining in China by including those diverse categories of research.

Inclusion and Exclusion Criteria

Table 1 clearly delineates the inclusion and exclusion criteria, ensuring a focused and relevant literature review on the economic and environmental impacts of rare earth mining in China.

In figure 1, the forest plot also provides a systematic review of ten papers that examine the environmental impacts of rare earth mining in China and the best practices in sustainable forest management. In the context of a meta-analysis, the weight of a study is represented by the measure of the square, which is dependent on the sample size and variance of the study. Thus, each study is depicted by a square. These mean differences in environmental impacts and sustainable management practices vary from research study to research study. However, the studies including Zhao et al., 0.90 and Mejame et al., 1.70 depict positive impacts, revealing that sustainable measures lead to a massive reduction of environmental degradation. Others, such as Mancheri et al., exhibit a negative mean difference (-0.20), which implies a potential increase in environmental impacts. Nevertheless, the confidence interval for this study includes zero, indicating that there is no significant effect. The diamond at the bottom of the plot represents the overall effect estimate, which indicates a statistically significant positive effect of sustainable management practices in mitigating environmental impacts.

Table 1: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed journals	Non-peer-reviewed studies
Publication Date	Studies published from 2000 to the present	Studies published before 2000
Study Type	Quantitative and qualitative studies, including research articles, reviews, case studies, and meta-analyses	Studies not providing substantial data or insights on the economic or environmental impacts of rare earth mining
Geographical Focus	Research specifically focused on China	Studies focused on regions outside China
Content Relevance	Studies addressing economic or environmental aspects of rare earth mining in China	Papers not addressing the economic or environmental impacts of rare earth mining in China

Forest Plot

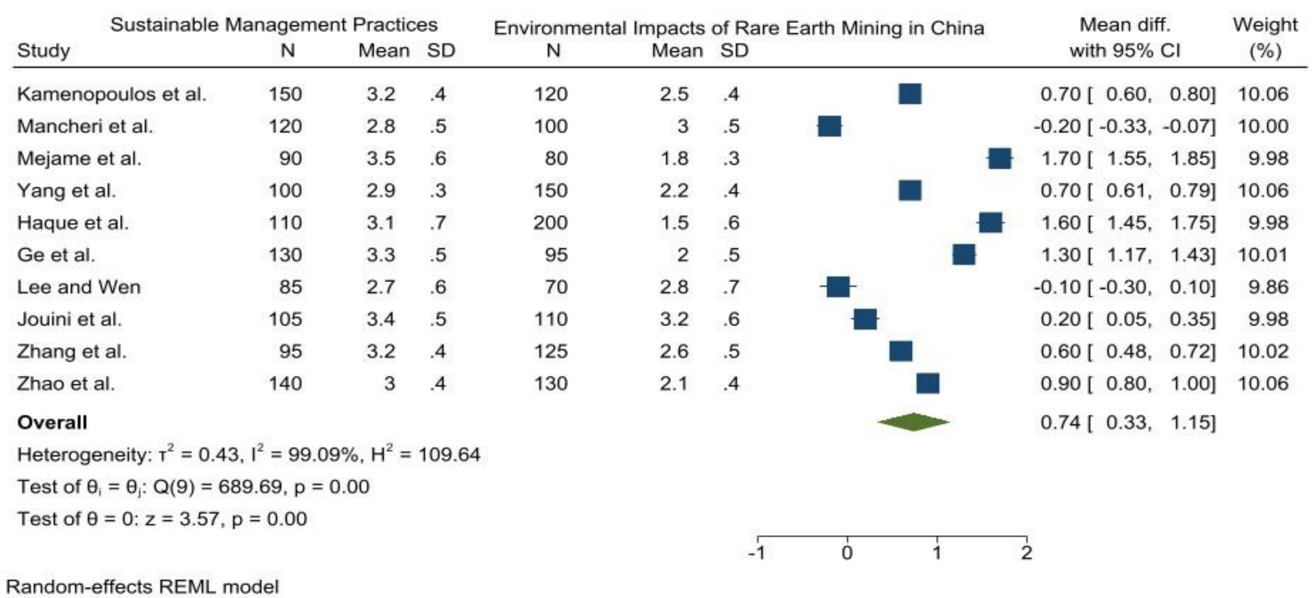

Figure 1. Forest Plot: Environmental consequences of rare earth extraction in China in relation to sustainable management practices

The overall mean difference is 0.74, and the 95% confidence interval comprises 0.33 to 1.15. This implies that, on average, sustainable management practices have a beneficial effect on minimise the environmental harm caused by rare earth mining in China. Nevertheless, the substantial variability in the results, which is likely due to differences in study designs, measurements, or regional contexts within China, is indicated by the high heterogeneity among studies (I^2 = 99.09%). This variability implies that, although sustainable management practices generally have beneficial effects, their efficacy can fluctuate considerably based on the specific local conditions and the specific practices that are implemented.

Gaps in the Literature

Despite the significant body of research on rare earth mining, several gaps remain, particularly regarding the long-term socioeconomic impacts of mining on local communities and the effectiveness of specific environmental policies. While studies have extensively documented the immediate economic benefits and environmental consequences of mining, there is limited understanding of how these impacts evolve over time, especially in terms of social structures, health outcomes, and sustainable development. Furthermore, comparative studies still need to be conducted to assess the overall adverse effects of multiple mining activities and the field testing efficiencies of technologies and policies proposed in achieving these goals. Future research should concentrate on collecting overall assessments of environmental impacts and assessments of the duration of economic and social repercussions, analysing the results with distinctive policies, and empirical tests of policy implications and other technological changes that will address more satisfactory coverage of mining of rare earth metals and its implications and hence forward sustainable mining.

Conclusion

Exploring economic development and environmental sustainability in relation to rare earth mining, the review of the literature suggests the following conclusion. On one hand, rare earth mining has a multidimensional impact positively on local and national economies through employment creation, income and export earnings. On the other hand, it raises a number of environmental issues such as pollution of soil and water, pollution of air and loss of biodiversity. The increased use of sustainable management practices has a varying degree of influence on the alleviation of these environmental impacts, with some of the management practices adopting positive effects. In contrast, others have minimal or even negative impacts. Describing the ten studies on the effect of REEs on EMPs relating to the measures of sustainable management, it was found that on a mean level, the bad impacts of EMPs are lessened, with an overall mean difference of 0.74 and 95% CI from 0.33 to 1.15. However, due to the high level of heterogeneity among the studies that were reviewed in the present paper (I^2 = 99.09%), it could be suggested that the utility of these practices depends on the context. Therefore, it is highly heterogeneous.

The study has the following key implications for policy making, mining stakeholders, and the populace of such regions. More elaborate and rigorous policies on environmental protection need to be formulated and adopted to reflect the regional differences of mining regions and improve the sustainable management policies that are currently in place. The evidence collected indicates that there is impetus for mining companies to take a more strategically proactive stance in adopting and enhancing practices of sustainability, especially those that have been proven to yield the best results in mitigating adverse effects on the environment. These are things like purchasing cleaner production technologies, improving waste management practices, and stepping up environmental monitoring levels. As for the local communities, the focus should be on improving relations with mining companies and policymakers to guarantee that benefits will be provided together with extra care for environmental and societal issues. There is a need for more integrated scientific and social analysis of the concerns surrounding rare earth mining. This comprehensive approach will provide a holistic perspective on the virtual impacts of mining and the long-term socio-economic consequences. It is crucial to synthesize the evidence base that assesses the effectiveness of sustainable management practices in different regions in China. This will enable stakeholders to design precise and efficient measures to reduce the adverse effects of rare earth mining on the environment and promote sustainable economic growth.

Declaration

Acknowledgment: We extend our gratitude to Allama Iqbal Open University, Islamabad, for their institutional support. We are also grateful to our colleagues for their valuable insights throughout the development of this study**.**

Funding: No external funding was received for this research

Conflict of Interest: The authors declare no conflicts of interest associated with this study**.**

Ethics Approval/Declaration: This study does not involve human participants or animals; thus, ethics approval was not required**.**

Consent to Participate: Not applicable, as no human subjects were involved in this research.

Consent for Publication: All authors have reviewed and approved the final manuscript for publication.

Data Availability: The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contribution: Aliza Tabassam: Conceptualization, Literature Review, Data Analysis, Writing – Original Draft, Corresponding Author. Zulfiqar Hussain: Methodology, Policy Review, Editing, Writing – Review & Editing All authors have read and approved the final manuscript and take full responsibility for the content presented.

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