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POST-COAL MINING VOIDS: ENVIRONMENTAL RISKS, UTILIZATION POTENTIAL, AND SUSTAINABILITY CHALLENGES: A REVIEW

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ABSTRACT

Open-pit coal mining generates extensive post-mining voids in the form of large depressions that pose persistent environmental challenges, including land degradation, water pollution, ecological imbalance, and long-term safety risks. At the same time, these voids offer substantial opportunities for productive and sustainable utilization when managed through integrated environmental strategies. This review aims to critically assess the opportunities, potentials, and challenges associated with the sustainable use of post-coal mining voids within the context of environmental protection and pollution control. A narrative review methodology was employed by systematically analyzing more than 80 international peer-reviewed articles published between 2010 and 2024, encompassing multidisciplinary case studies from various countries. The findings indicate that unmanaged mining voids significantly contribute to acid mine drainage, water quality deterioration, and landscape instability, whereas integrated reclamation approaches can restore ecological and hydrological functions. Technologies such as floating photovoltaic systems, pressure retarded osmosis, and spatially based hydrological modeling demonstrate strong potential in supporting renewable energy generation, water resource management, and land rehabilitation in former mining areas. The review further highlights the importance of regulatory enforcement, technological innovation, and community engagement in ensuring sustainable post-mining transitions. Overall, this study concludes that post-coal mining voids can be transformed from environmental liabilities into strategic assets that support environmental sustainability, pollution mitigation, and the achievement of the Sustainable Development Goals, particularly those related to clean water, clean energy, climate action, and ecosystem restoration.

KEYWORDS: Post-Coal Mining Voids; Mine Reclamation; Environmental Pollution; Renewable Energy Utilization; Floating Photovoltaic Systems; Sustainable Land Management; Energy Transition; Former Mine Land Utilization.

1. INTRODUCTION

Open-pit coal mining remains the dominant extraction method in many coal-producing countries, including Indonesia, due to its technical simplicity and economic efficiency in exploiting shallow coal seams (Wehnert et al. 2019; Sardjono et al. 2023). However, this method generates extensive environmental disturbances, particularly through large-scale land stripping, landscape deformation, ecosystem fragmentation, and long-term safety risks (Liu et al. 2025; Dale et al. 2005; Chaudhary et al. 2020). The removal of overburden layers alters land morphology and often results in land subsidence and unstable slopes, while exposed coal seams increase the risk of spontaneous combustion and underground coal fires (Wang et al. 2022). Beyond physical degradation, open-pit mining significantly disrupts hydrological systems, altering surface runoff patterns, groundwater flow, and water storage capacity, thereby contributing to broader environmental burdens after mine closure (Winde 2020).

One of the most prominent legacies of open-pit coal mining is the formation of mine voids, defined as large depressions left after coal extraction. These voids often reach considerable depths and widths and gradually fill with rainwater and surface runoff, forming pit lakes or former mine lakes (Wu et al. 2019; Lian et al. 2021; Tuheteru et al. 2021). While visually striking, such voids present complex environmental challenges, including slope instability, water contamination, and long-term reclamation difficulties due to their scale and geotechnical characteristics. These risks have direct implications for public health and urban safety, particularly when mine voids are located near settlements or expanding urban areas, linking post-mining management to sustainable city development and human well-being.

From a hydro chemical perspective, post-mining voids are frequently associated with severe water quality degradation. Oxidation of sulphide-bearing minerals, especially pyrite, leads to acid mine drainage (AMD), which increases acidity and mobilizes heavy metals into groundwater and surface water systems (Dong et al. 2020). Studies from China, India, and Australia demonstrate that post-mining environments often transition from reducing to oxidizing conditions, resulting in elevated concentrations of iron, manganese, and other toxic elements that persist long after mine closure (Dong et al. 2020; Coffey Services Australia Pty Ltd. 2021). If left unmanaged, such voids become long-term sources of environmental pollution, posing risks to aquatic ecosystems, agricultural water use, and downstream communities.

Despite these challenges, growing evidence suggests that post-coal mining voids also offer significant opportunities for sustainable reuse when integrated into comprehensive reclamation strategies. Traditional reclamation approaches, such as revegetation and land contouring, have shown limited effectiveness in deep and expansive voids due to high costs and technical constraints (Singh et al. 2024). Consequently, innovative land-use strategies have emerged, including ecotourism development, aquaculture, biodiversity conservation, and renewable energy production, transforming voids from environmental liabilities into multifunctional assets (Singh et al. 2024; Brodny and Tutak 2022). These approaches align with global sustainability agendas by simultaneously addressing environmental rehabilitation and socio-economic revitalization.

Among emerging solutions, renewable energy technologies have gained increasing attention as viable options for post-mining void utilization. Water-filled voids are particularly suitable for floating photovoltaic (FPV) systems, which offer advantages such as reduced land-use conflict, enhanced panel efficiency due to evaporative cooling, and reduced water evaporation (Pouran et al. 2022). Empirical studies indicate that large-scale FPV installations have minimal adverse impacts on water quality, with only minor changes in surface temperature and biofouling observed (de Lima et al. 2021). In parallel, technologies such as Pressure Retarded Osmosis (PRO), reverse electrodialysis, and geothermal energy extraction from mine water have been proposed as innovative pathways for clean energy generation in former mining landscapes (Winde 2020; Golroodbari et al. 2021).

Beyond technical feasibility, the sustainable utilization of mine voids requires integrated governance frameworks that consider ecological, social, and regulatory dimensions. GIS-based spatial analysis and multi-criteria decision-making tools have been widely applied to identify optimal locations for renewable energy deployment while balancing environmental sensitivity and economic viability (Velaz-Acera et al. 2024). However, several studies emphasize that regulatory uncertainty, water contamination risks, and long-term geotechnical stability remain major barriers to implementation (Agboola et al. 2020; Khayrutdinov et al. 2022). In Indonesia, where coal mining is concentrated in Kalimantan and Sumatra, the absence of robust post-mining governance and inconsistent reclamation enforcement further complicate the sustainable reuse of mining voids (Pratiwi et al. 2021).

Although numerous studies have examined individual aspects of post-mining void management, such as water quality, ecological restoration, or renewable energy deployment, a comprehensive synthesis integrating environmental risks, utilization potential, and sustainability challenges remains limited, particularly in the context of developing countries. Previous research often addresses technical or ecological dimensions in isolation, without fully integrating socio-economic implications, policy frameworks, and alignment with the Sustainable Development Goals (SDGs). Therefore, this review is significant in addressing this research gap by providing an integrated assessment of post-coal mining voids as both environmental challenges and strategic opportunities. The aim of this study is to critically review global experiences and best practices in the utilization of post-coal mining voids, with a focus on renewable energy development, environmental restoration, and sustainable land management, and to derive evidence-based insights relevant for policy formulation and implementation in Indonesia.

Unlike previous reviews that focus primarily on environmental remediation or isolated reuse strategies, this study provides an integrative synthesis that connects environmental risks, technological utilization potential, governance challenges, and sustainability transitions within a unified analytical perspective. By systematically reviewing more than 80 international studies (2010–2024), this paper highlights three main contributions: (1) a consolidated risk framework for post-coal mining voids, (2) a comparative evaluation of sustainable utilization pathways including renewable energy integration, and (3) a policy-oriented roadmap linking void management to the Sustainable Development Goals (SDGs). This integrative approach positions post-mining voids not merely as environmental liabilities, but as transitional landscapes with strategic sustainability potential.

2. METHODOLOGY OF REVIEW

The review process was guided by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) principles to ensure transparency and reproducibility. This study adopts a narrative review methodology with a structured and transparent literature selection process to synthesize current knowledge on the opportunities, potentials, and challenges associated with post-coal mining void utilization. A narrative review approach was selected because the research objective is not merely to map existing literature, but to critically interpret, compare, and integrate findings across technical, ecological, social, and policy dimensions. Previous studies on mine voids often focus on isolated aspects such as water quality (Dong et al. 2020), renewable energy applications (Pouran et al. 2022), or reclamation ecology (Gao et al. 2022). In contrast, this review aims to develop an integrated understanding that supports sustainable post-mining land use planning, particularly in the context of energy transition and environmental governance.

2.1. Study Screening and Selection Process

The literature search initially identified 214 records across Scopus, Web of Science, and Google Scholar databases. After removing 38 duplicate records, 176 articles remained for title and abstract screening. Based on relevance to post-coal mining voids, environmental risks, utilization potential, and sustainability aspects, 72 articles were excluded at this stage. The full texts of the remaining 104 articles were then assessed for eligibility using predefined inclusion criteria (peer-reviewed publications, English language, empirical or review studies, and clear relevance to pit lake management).

During the full-text assessment, 21 articles were excluded due to insufficient methodological clarity or limited relevance to post-coal mining void sustainability. Finally, 83 studies published between 2010 and 2024 were included in the qualitative synthesis and thematic analysis. A PRISMA-style flow diagram summarizing the identification, screening, eligibility, and inclusion stages is presented in Figure X to enhance methodological transparency.

2.2. Review Design

The review design follows a thematic narrative synthesis, enabling the comparison of empirical findings, conceptual frameworks, and policy-oriented studies. This approach allows flexibility in interpreting diverse case studies from different geographical and regulatory contexts, including Indonesia, China, Australia, India, Poland, and South Africa. Unlike scoping reviews that emphasize breadth over depth, the chosen design prioritizes analytical depth and contextual relevance, especially for countries with extensive post-coal mining legacies. This design is consistent with previous narrative reviews addressing post-mining land use and environmental recovery (Winde 2020; Pavloudakis et al. 2020).

2.3. Literature Search Strategy

A comprehensive literature search was conducted using major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search covered peer-reviewed journal articles published between 2010 and 2024, ensuring the inclusion of both foundational studies and recent technological innovations. Key search terms included combinations of coal mine voids, pit lakes, post-mining land use, floating photovoltaic, renewable energy, mine water management, reclamation, and sustainable development. To enhance contextual relevance, additional keywords related to Indonesia and Southeast Asia were incorporated. Reference lists of selected articles were also examined to identify additional relevant studies.

2.4. Inclusion and Exclusion Criteria

Articles were included if they met the following criteria: (i) addressed post-coal mining voids or pit lakes resulting from open-pit mining; (ii) discussed utilization, reclamation, or management strategies; (iii) examined technical, environmental, socio-economic, or policy aspects; and (iv) were published in peer-reviewed journals in English. studies focusing exclusively on underground mining voids, non-coal minerals, or lacking relevance to post-mining land use were excluded. grey literature, reports, and conference papers were only considered when they provided critical contextual or regulatory insights, particularly for Indonesia, and when peer-reviewed sources were limited.

2.5. Data Extraction and Thematic Analysis

Relevant information from each selected study was systematically extracted, including geographical context, void characteristics, utilization strategy, environmental impacts, technical feasibility, socio-economic implications, and governance frameworks. the extracted data were then organized into major thematic categories: (i) environmental and hydrological impacts of mine voids, (ii) renewable energy applications including floating photovoltaic, pressure retarded osmosis, and geothermal use of mine water, (iii) ecological reclamation and biodiversity restoration, and (iv) socio-economic and policy challenges. this thematic synthesis enabled cross-comparison of findings and identification of recurring patterns and contradictions across regions, as recommended by Singh et al. (2024) and Brodny and tutak (2022).

2.6. Analytical Framework

To ensure coherence with global sustainability agendas, the analysis was framed within the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). The framework integrates technical feasibility, environmental risks, socio-economic benefits, and governance considerations, reflecting the multidimensional nature of post-mining land use decisions. This integrative framework addresses a key limitation of earlier studies that often-examined void utilization from a single disciplinary perspective. By combining insights from engineering, environmental science, and policy studies, this review provides a comprehensive basis for evidence-based recommendations supporting sustainable post-mining management in Indonesia and comparable regions.

Figure 1 presents the conceptual framework of this review, highlighting the transformation of post-coal mining voids from environmental liabilities into sustainable assets through integrated technological, ecological, socio-economic, and governance-based approaches. Open-pit coal mining leaves behind large voids that function as long-term environmental liabilities due to land degradation, water contamination, and safety risks. Without proper management, these voids exacerbate ecological degradation and impose significant socio-economic burdens on surrounding communities, as highlighted by previous studies (Dong et al. 2020; Winde 2020).

The framework positions renewable energy technologies as a central intervention strategy, particularly floating photovoltaic systems, Pressure Retarded Osmosis, and geothermal utilization of mine water. These technologies enable the productive use of water-filled voids without competing for agricultural or urban land, while simultaneously supporting clean energy transitions (Pouran et al. 2022; Velaz-Acera et al. 2024). Technological interventions are complemented by environmental and ecological restoration measures, including water quality management, hydrological modeling, and ecosystem-based reclamation, which are essential to mitigate acid mine drainage and restore ecological functions (Gao et al. 2022).

The framework further integrates socio-economic utilization pathways, such as ecotourism and aquaculture, which enhance local livelihoods and promote community engagement. These pathways align with the growing recognition that post-mining reclamation must extend beyond biophysical restoration to include social and economic revitalization (Singh et al. 2024). Governance and policy mechanisms form the enabling foundation of the framework, emphasizing the role of reclamation regulations, ESG principles, and multi-stakeholder collaboration in ensuring long-term sustainability and risk management (Ren et al. 2024).

Overall, the framework demonstrates how integrated management strategies can transform post-coal mining voids into sustainable landscapes that contribute to climate mitigation, clean energy production, and socio-economic resilience. By aligning these outcomes with the Sustainable Development Goals, the framework provides a holistic basis for evidence-based policy development and strategic planning, particularly for coal-dependent regions such as Indonesia.

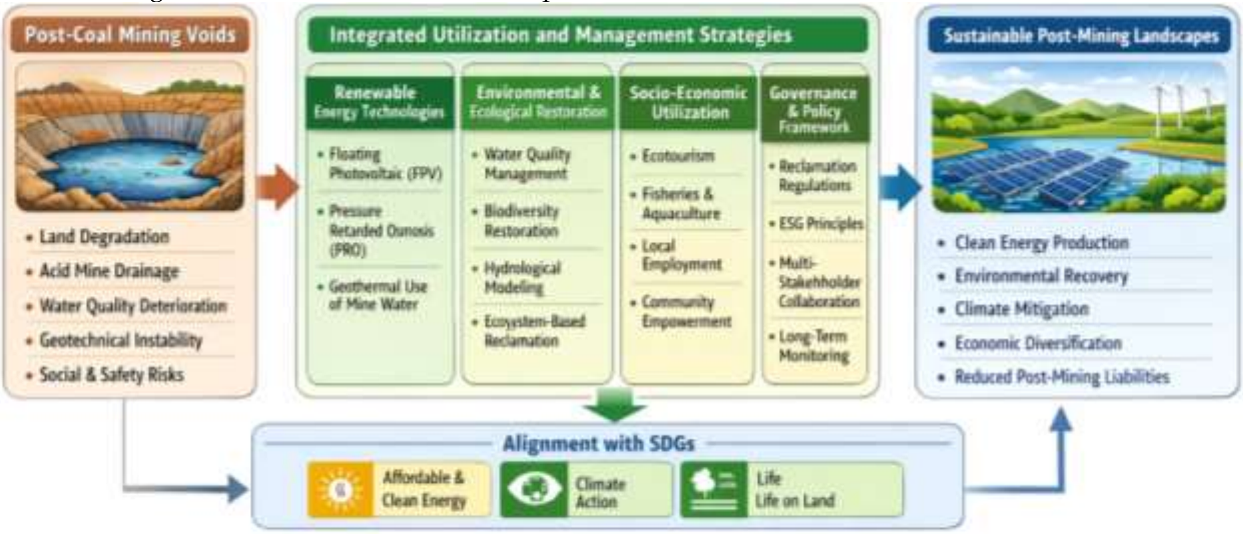

Figure 1. Conceptual framework of this review, highlighting the transformation of post-coal mining voids from environmental liabilities into sustainable assets through integrated technological, ecological, socio-economic, and governance-based approaches.

Grey literature, including governmental reports and institutional publications, was considered selectively to provide contextual information on regulatory frameworks and national policies. However, only documents issued by recognized institutions (e.g., government agencies, international organizations, or accredited research institutes) were included. These sources were evaluated based on credibility, transparency of data sources, and consistency with peer-reviewed findings to ensure academic reliability. All methodological clarifications and formatting refinements suggested during the review process have been incorporated to improve transparency, consistency, and academic rigor.

3. OPPORTUNITIES OF POST-COAL MINING VOIDS

Post-coal mining voids are often regarded as environmental liabilities due to their association with land degradation, water pollution, and safety risks. however, a growing body of literature suggests that these voids can be transformed into strategic assets through sustainable planning, technological innovation, and integrated governance frameworks (Brodny and Tutak 2022; Worden et al. 2024). instead of viewing voids solely as reclamation burdens, recent studies emphasize their potential role in supporting renewable energy transitions, ecological restoration, and socio-economic development, particularly in regions undergoing post-mining economic restructuring. this paradigm shift aligns with global sustainability agendas and the transition toward low-carbon and circular land-use systems (Spasić et al. 2023).

3.1. Renewable Energy Utilization in Post-Mining Voids

Water-filled post-mining voids present highly favourable conditions for renewable energy development, particularly floating photovoltaic (FPV) systems. FPV technology allows solar energy generation without competing for productive land, which is especially critical in densely populated or agricultural regions (Benjamins et al. 2024). Compared with land-based photovoltaic installations, FPV systems benefit from the natural cooling effect of water surfaces, leading to lower panel operating temperatures and higher energy conversion efficiency (Velaz-Acera et al. 2024). Empirical studies conducted in China, India, and Europe demonstrate that FPV installations on former mining lakes can achieve higher performance ratios while simultaneously reducing water evaporation and mitigating algal blooms (Pouran et al. 2024).

Several comparative studies further highlight the economic feasibility of FPV systems in mining voids. Koondhar et al. (2024) reported that FPV systems in water-scarce regions exhibited greater energy yield stability than ground-mounted PV, particularly under high-temperature conditions. However, infrastructure costs—especially anchoring and mooring systems—remain a critical consideration. For instance, Pouran et al. (2024) documented anchoring costs of approximately 10 USD/kW in a 70 MW FPV project implemented on a flooded coal mine in Anhui, China, indicating that site-specific hydrological and geotechnical conditions strongly influence project viability.

Beyond standalone solar systems, post-mining voids also offer opportunities for hybrid renewable energy systems (HRES) that integrate solar and wind energy. Hybrid configurations can enhance energy reliability and mitigate intermittency challenges inherent to single-source systems (Ramesh et al. 2020). Pérez Uc et al. (2024) demonstrated that combining floating PV with nearby wind installations significantly improved capacity factors and reduced reliance on centralized power grids. Such systems are particularly relevant for remote post-mining regions, where grid access is limited and energy security is a critical development priority.

3.2. Ecological Restoration and Biodiversity Enhancement

Post-coal mining voids also provide substantial opportunities for ecological restoration and biodiversity enhancement. When managed appropriately, these areas can be converted into artificial lakes, wetlands, or reforested landscapes that support habitat recovery and ecosystem services (Rahmonov et al. 2022). Studies on mine reclamation consistently emphasize the importance of using native or endemic plant species to accelerate soil stabilization, improve nutrient cycling, and promote long-term ecological resilience (Prawitra Thalib et al. 2020).

Comparative ecological studies indicate that void-based restoration initiatives can support diverse plant and aquatic communities, particularly when reclamation strategies are guided by ecological succession principles (Gao et al. 2022). Faur et al. (2023) showed that post-mining lakes, when integrated into broader landscape restoration plans, can function as biodiversity refuges and contribute to regional ecological connectivity. These findings underscore the potential of post-mining voids to transition from degraded landscapes into functional ecological systems, supporting SDG 15 (Life on Land) and SDG 6 (Clean Water and Sanitation).

3.3. Socio-Economic Integration and Community Development

From a socio-economic perspective, post-mining voids offer opportunities for community-based development and economic diversification. Several studies document the successful transformation of former mining voids into ecotourism destinations, recreational parks, fisheries, and educational sites that highlight environmental restoration and mining heritage (Xu et al. 2023). Such initiatives not only generate alternative income streams but also foster local employment and strengthen community engagement in post-mining land management.

Comparative evidence from China, Australia, and Eastern Europe suggests that ecotourism and multifunctional land-use strategies can significantly improve public perception of mining legacies while enhancing local economic resilience (Worden et al. 2024). Moreover, integrating local communities into planning and management processes has been shown to increase the long-term sustainability of post-mining projects, aligning with SDG 8 (Decent Work and Economic Growth) and SDG 11 (Sustainable Cities and Communities).

3.4. Technological Innovation and Digitalization

Advances in digital technologies have further expanded opportunities for optimizing post-coal mining void utilization. Geographic Information Systems (GIS), remote sensing, and three-dimensional (3D) modelling enable detailed spatial analysis and scenario-based planning for reclamation and redevelopment projects (Menéndez et al. 2020). These tools allow stakeholders to evaluate hydrological behaviour, slope stability, land suitability, and environmental risks with greater precision.

Recent studies highlight that GIS-based multi-criteria decision analysis (MCDA) frameworks are particularly effective for identifying optimal sites for renewable energy installations, ecological restoration, and mixed land-use development (Servou et al. 2023). By integrating environmental, technical, and socio-economic variables, digital decision-support systems enhance transparency and reduce uncertainty in post-mining land management, contributing to evidence-based policymaking.

3.5. Policy, Governance, and ESG-Oriented Opportunities

Policy and governance frameworks play a pivotal role in unlocking the opportunities associated with post-coal mining voids. Effective collaboration among governments, mining companies, and local communities is essential to ensure that void utilization aligns with environmental standards and social expectations (Dong et al. 2021). Comparative policy analyses reveal that countries with clear post-mining land-use regulations and incentive mechanisms are more successful in transforming voids into sustainable assets.

The increasing prominence of Environmental, Social, and Governance (ESG) principles further strengthens the case for sustainable post-mining projects. Litvinenko et al. (2022) argue that ESG-driven investment frameworks can accelerate decarbonization and promote responsible resource management, despite challenges related to regulatory legitimacy and cost escalation. Complementary studies by Woods et al. 2022 and Nordström 2022 demonstrate that integrating ESG principles into post-mining land-use planning enhances long-term environmental outcomes and improves corporate accountability. Consequently, ESG-oriented governance presents a strategic opportunity to align post-coal mining void utilization with global sustainability goals and energy transition pathways.

4. POTENTIAL OF POST-COAL MINING VOIDS

Beyond immediate opportunities, post-coal mining voids possess substantial long-term potential to support sustainable land-use transformation and post-mining economic restructuring. Recent studies emphasize that innovative post-mining land uses (PMLUs) can generate enduring social, economic, and environmental value when rehabilitation strategies move beyond short-term compliance toward integrated sustainability planning (Morton et al. 2024). Redirecting reclamation investments into multifunctional land-use systems enables post-mining regions to reduce environmental liabilities while contributing to decarbonization and regional development agendas.

4.1. Infrastructure and Environmental Service Potential

Post-mining voids offer significant potential as foundations for critical infrastructure and environmental services. Due to their large spatial extent and hydrological capacity, voids can be repurposed as water storage facilities, flood control reservoirs, or integrated water management systems supporting agriculture and industry (Onsulting SRK 2019). Łupieżowiec et al. (2022) further argue that, under strict environmental safeguards, certain voids may serve as secure containment sites for specific waste streams, thereby reducing land pressure elsewhere. When supported by robust geotechnical and hydro chemical assessments, such applications can contribute to circular land-use strategies and sustainable infrastructure development.

4.2. Energy Transition and Innovation Potential

A major source of potential lies in positioning post-mining voids as hubs for clean energy innovation. Comparative studies demonstrate that voids are increasingly utilized for floating photovoltaic (FPV) installations, hybrid renewable systems, and emerging technologies such as Pressure Retarded Osmosis (PRO) and green hydrogen production (Pouran et al. 2022; Winde 2020; Sikora et al. 2024). These applications illustrate how voids can transition from environmental burdens into strategic assets supporting national energy transitions. Unlike conventional renewable installations, void-based energy systems minimize land-use conflicts while leveraging existing mining-altered landscapes, making them particularly suitable for densely populated or ecologically sensitive regions.

4.3. International Experiences and Comparative Potential

Empirical evidence from multiple countries demonstrates diverse pathways for harnessing the potential of post-mining voids. As summarized in Table 1, countries such as Indonesia, China, India, Spain, South Africa, and Poland have adopted context-specific approaches integrating renewable energy, water management, and ecological functions. These comparative cases highlight that successful utilization depends on site-specific characteristics, regulatory frameworks, and technological readiness rather than a one-size-fits-all solution.

As shown in Table 1, international experiences demonstrate that post-mining voids can accommodate a wide spectrum of sustainable functions, ranging from renewable energy generation to advanced water-energy systems. Comparative analysis reveals that FPV systems dominate current applications due to their technological maturity, while emerging innovations such as green hydrogen and osmotic power represent future-oriented potential requiring further pilot-scale validation (Pouran et al. 2022; Sikora and Kochanowski 2024).

Table 1: Environmental Risks Associated with Post-Coal Mining Voids.

Country	Void Location	Mining Type	Estimated Area / Capacity	Primary Utilization Strategy	References
Indonesia	J-void, East Kalimantan	Open-pit coal	~300 ha	Pit lake formation and floating solar PV	Tuheteru et al. 2021
China	Huainan subsidence pond	Coal	n/a	Floating PV with water quality monitoring	Wang et al. 2022
India	Jharkhand coalfield	Coal	96 MW (installed capacity)	Hybrid floating PV and hydropower	Singh et al. 2024
Spain	Central region former mine lake	Mixed mining	n/a	GIS-based FPV site optimization	Velaz-Acera et al. 2024
South Africa	Abandoned gold mine void	Gold	n/a	Pressure Retarded Osmosis (PRO) energy	Winde 2020
Poland	West Pomerania	Sand and gravel excavation	n/a	Green hydrogen production via FPV	Sikora and Kochanowski 2024

4.4. Alignment with Sustainable Development Goals

The potential of post-coal mining voids is strongly linked to their contribution toward achieving the Sustainable Development Goals (SDGs). Integrated utilization strategies enable voids to simultaneously address clean energy access, water security, climate mitigation, biodiversity restoration, and sustainable urban development. Studies consistently show that aligning reclamation planning with the SDG framework enhances policy coherence and improves long-term project sustainability (Velaz-Acera et al. 2024; Faur et al. 2024).

Table 2 illustrates that post-mining void utilization strategies extend beyond single-sector benefits and can simultaneously contribute to multiple SDGs. Compared with traditional reclamation practices focused solely on land stabilization, SDG-aligned approaches enable post-mining landscapes to function as multifunctional systems that deliver environmental services, economic opportunities, and social benefits (Morton et al. 2024).

Table 2: Sustainable Utilization Options for Post-Coal Mining Voids.

Void Utilization Strategy	Primary SDG Alignment	Supporting Evidence
Floating photovoltaic systems	SDG 7 – Affordable and Clean Energy	Pouran et al. 2022; Velaz-Acera et al. 2024
Biodiversity and habitat restoration	SDG 15 – Life on Land	Faur et al. 2024
Mine lake water management	SDG 6 – Clean Water and Sanitation	Winde 2020
Green hydrogen production	SDG 13 – Climate Action	Sikora and Kochanowski 2024
Ecotourism and environmental education	SDG 11 – Sustainable Cities and Communities	Singh et al. 2024

4.5. Synthesis of Potential and Strategic Implications

Overall, the potential of post-coal mining voids lies in their capacity to support integrated, future-oriented land-use systems that combine infrastructure development, energy transition, ecological restoration, and socio-economic revitalization. While previous studies often addressed individual applications in isolation, recent evidence underscores the importance of holistic frameworks that align technological innovation with sustainability principles and governance mechanisms (Łupieżowiec et al. 2022; Velaz-Acera et al. 2024). Harnessing this potential requires coordinated planning, adaptive regulation, and long-term monitoring to ensure that post-mining voids evolve into resilient assets rather than persistent environmental risks.

4.6. Challenges And Limitations Of Post-Coal Mining Void Utilization

Despite their considerable opportunities and long-term potential, post-coal mining voids present complex challenges that must be addressed to ensure safe, sustainable, and socially acceptable utilization. Previous studies consistently emphasize that without rigorous planning and risk mitigation, post-mining voids may evolve into long-term environmental liabilities rather than development assets (Pagouni et al. 2024; Worden et al. 2024). These challenges are multidimensional, encompassing technical constraints, environmental risks, socio-economic concerns, and regulatory limitations.

4.6.1. Synthesis of Potential and Strategic Implications

One of the most critical challenges in post-mining void utilization is ensuring structural stability and operational safety. Post-mining landscapes are often characterized by unstable slopes, heterogeneous backfill materials, and unpredictable geotechnical conditions, increasing the risk of landslides, subsidence, and infrastructure failure (Khayrutdinov et al. 2022). These risks are particularly pronounced when voids are repurposed for public access uses such as ecotourism or recreational facilities. Konieczna-Fuławka et al. (2023) identify post-mining tourism sites as among the highest-risk environments due to combined physical, chemical, and ergonomic hazards, including unstable terrain, water-related accidents, and exposure to hazardous substances.

In addition, the technical feasibility of renewable energy installations in voids is constrained by site-specific factors such as water depth, sedimentation rates, wind exposure, and anchoring system requirements. While FPV systems have demonstrated technical viability, studies show that anchoring and mooring systems account for a significant proportion of capital costs and require continuous maintenance to ensure long-term performance (Pouran et al. 2024). These technical challenges underscore the importance of detailed geotechnical and hydrological assessments prior to implementation.

4.6.2. Environmental and Ecological Constraints

Environmental risks remain a major limitation in the utilization of post-coal mining voids. Soil and water contamination by heavy metals and acid mine drainage (AMD) pose persistent threats to ecosystems and human health (Rouhani et al. 2023). These contaminants originate from the oxidation of sulphide minerals, coal ash disposal, and residual mining waste, and may remain active for decades if not properly managed. Comparative studies reveal that unclaimed voids often exhibit elevated concentrations of iron, manganese, and other toxic elements, limiting their suitability for ecological restoration or water-related applications (Dong et al. 2020).

Although reclamation techniques such as phytoremediation and water treatment systems can mitigate these impacts, their effectiveness varies depending on site conditions and long-term maintenance commitments. Faur et al. (2024) emphasize that ecological restoration in post-mining environments requires sustained monitoring and adaptive management, as premature interventions may fail to establish stable ecosystems. Consequently, environmental uncertainty remains a significant constraint in scaling up void utilization projects.

4.6.3. Socio-Economic and Community-Related Challenges

Socio-economic factors also shape the feasibility of post-mining void utilization. While projects such as ecotourism and renewable energy development offer employment opportunities, they may face resistance from local communities due to safety concerns, limited awareness, or mistrust toward mining companies (Adesipo et al. 2021). Studies highlight that inadequate community engagement can lead to social conflicts and undermine the long-term success of post-mining projects (Xu et al. 2023).

Furthermore, the economic viability of void-based projects is often sensitive to market conditions, energy prices, and financing availability. High initial investment costs, coupled with uncertain returns, may deter private sector participation, particularly in regions with limited institutional capacity (Litvinenko et al. 2022). As a result, many voids are classified as non-use management areas (NUMAs), where rehabilitation is minimized due to economic constraints rather than environmental suitability (Worden et al. 2024).

4.6.4. Regulatory and Governance Limitations

Regulatory and governance frameworks represent another critical challenge. Historically, surface mine land reclamation was not systematically regulated, leading to widespread abandonment of mining voids prior to the 1960s (Pagouni et al. 2024). Although environmental regulations became stricter from the 1970s onward, implementation remains uneven across countries and regions. In many developing economies, regulatory gaps, limited enforcement capacity, and unclear post-closure responsibilities hinder sustainable void utilization (Ren et al. 2024).

Additionally, the growing emphasis on Environmental, Social, and Governance (ESG) principles introduces both opportunities and constraints. While ESG frameworks encourage responsible post-mining practices, Litvinenko et al. (2022) argue that ESG mechanisms often lack legal enforceability and may increase operational costs by up to 60%, particularly for mining companies operating in transitional economies. Without clear policy incentives and harmonized standards, ESG-driven projects may struggle to achieve financial and regulatory viability.

4.6.5. Synthesis of Challenges and Strategic Implications

In summary, the utilization of post-coal mining voids is constrained by interrelated technical, environmental, socio-economic, and regulatory challenges. Comparative evidence from previous studies suggests that isolated interventions are insufficient to address these limitations. Instead, integrated planning frameworks that combine risk-based engineering, environmental remediation, community engagement, and adaptive governance are required to unlock the full potential of post-mining voids (Pagouni et al. 2024; Rouhani et al. 2023). Addressing these challenges is essential not only to minimize long-term environmental liabilities but also to ensure that post-mining void utilization contributes meaningfully to sustainable development and the global energy transition.

4.7. Policy And Management Implications

The synthesis presented in this review demonstrates that post-coal mining voids represent complex socio-ecological systems rather than isolated environmental problems. The interaction between acid mine drainage formation, heavy metal mobilization, hydrological instability, and governance limitations creates a multidimensional risk structure. However, when supported by appropriate regulatory frameworks, environmental monitoring, and technological innovation, these voids may transition into productive landscapes. The integration of floating photovoltaic systems, controlled aquaculture, eco-tourism, and water storage infrastructure reflects an emerging paradigm shift from remediation-focused management toward sustainability-oriented transformation. This transition aligns with SDGs 6 (Clean Water), 7 (Affordable and Clean Energy), 12 (Responsible Consumption), 13 (Climate Action), and 15 (Life on Land).

The sustainable utilization of post-coal mining voids requires a coherent policy framework that integrates environmental protection, energy transition objectives, and socio-economic development. Previous studies emphasize that fragmented or sector-specific policies often fail to address the complex, multi-dimensional nature of post-mining landscapes (Winde 2020; Morton et al. 2024). Therefore, governments should adopt integrated post-mining land-use policies that explicitly recognize mine voids as strategic assets rather than residual liabilities. Such policies should align reclamation planning with national sustainability agendas, climate commitments, and the Sustainable Development Goals, particularly SDGs 6, 7, 13, and 15.

From a governance perspective, multi-level and multi-stakeholder models are essential for effective post-mining void management. Comparative experiences from Australia, China, and the European Union indicate that successful reclamation and reuse are driven by collaboration among government agencies, mining companies, local communities, and research institutions (Worden et al. 2024; Velaz-Acera et al. 2024). Establishing dedicated post-mining authorities or inter-agency task forces can improve coordination, clarify post-closure responsibilities, and ensure continuity in long-term monitoring. Community participation should be institutionalized through consultation mechanisms to enhance social acceptance and reduce conflicts, as highlighted by Xu et al. (2023).

Economic instruments and regulatory incentives play a critical role in translating policy objectives into implementation. Studies show that financial mechanisms such as green subsidies, tax incentives, and blended finance schemes can significantly improve the economic feasibility of void-based renewable energy and ecological restoration projects (Litvinenko et al. 2022; Sikora et al. 2024). At the same time, clear liability and bonding regulations are needed to ensure that mining companies internalize post-closure costs. Strengthening Environmental, Social, and Governance (ESG) reporting requirements, while harmonizing them with national legal frameworks, can further encourage responsible corporate behaviour without creating excessive regulatory burdens.

In terms of implementation, a phased and data-driven roadmap is recommended to manage uncertainties and risks. Initial phases should focus on comprehensive site assessments, including geotechnical stability, hydro chemical conditions, and ecological baseline studies (Rouhani et al. 2023; Khayrutdinov et al. 2022). Pilot projects, particularly for technologies such as floating photovoltaic systems or hybrid renewable energy installations, can serve as learning platforms before large-scale deployment (Pouran et al. 2022). Subsequent phases should integrate adaptive management and long-term monitoring to ensure environmental safety and operational performance over time.

Overall, policy and management strategies for post-coal mining voids must move beyond compliance-oriented reclamation toward strategic, future-oriented land-use planning. Lessons from international best practices demonstrate that integrated governance models, supportive economic instruments, and phased implementation frameworks are key to unlocking the long-term value of post-mining voids (Morton et al. 2024; Winde 2020). For countries with extensive coal mining legacies such as Indonesia, embedding these principles into national post-mining policies can transform voids into drivers of clean energy transition, environmental restoration, and sustainable regional development.

4.8. Synthesis And Future Research Directions

This review synthesizes evidence showing that post-coal mining voids, while often abandoned and perceived as environmental liabilities, possess substantial potential to be transformed into strategic assets supporting sustainable development. Across diverse geographical contexts, previous studies demonstrate that voids can be repurposed for renewable energy generation, ecological restoration, water resource management, and socio-economic revitalization when supported by appropriate governance and technological frameworks (Winde 2020; Morton et al. 2024). However, the persistence of unmanaged and illegally created voids highlights a critical implementation gap between regulatory obligations and on-ground practices, particularly in regions with limited enforcement capacity.

Future research should prioritize the optimization of renewable energy systems tailored to post-mining landscapes. While floating photovoltaic systems have been widely studied, limited attention has been given to hybrid configurations that combine FPV with ground-mounted solar installations or other renewable sources such as wind and hydropower (Pouran et al. 2022; Singh et al. 2024). Empirical studies evaluating long-term performance, grid integration, and life-cycle environmental impacts of hybrid systems in reclaimed mining areas are needed to strengthen the evidence base for large-scale deployment.

Beyond energy applications, post-mining voids offer underexplored opportunities for ecological innovation. Research on artificial habitats, biodiversity corridors, freshwater aquaculture, and eco-tourism suggests that voids can support multifunctional ecosystems if ecological design principles are integrated from the planning stage (Faur et al. 2024; Xu et al. 2023). Future studies should adopt interdisciplinary approaches that link ecological monitoring with socio-economic assessments to better understand trade-offs between conservation objectives and livelihood generation for local communities.

Advancements in digital technologies present promising directions for improving void management and monitoring. The integration of Geographic Information Systems (GIS), 3D landscape modeling, and Internet of Things (IoT)-based sensors can enable real-time monitoring of water quality, slope stability, and infrastructure performance (Menendez et al. 2020; Velaz-Acera et al. 2024). However, empirical research assessing the scalability, cost-effectiveness, and governance implications of digitalized post-mining management systems remains limited and warrants further investigation.

Finally, future research should focus on governance innovation and ESG-oriented frameworks to support inclusive and accountable void utilization. While ESG principles are increasingly adopted in the mining sector, their application in post-mining land use remains uneven and often lacks legal clarity (Litvinenko et al. 2022). Comparative policy studies and cross-country case analyses can help identify role-model projects and transferable best practices. Such research is essential for developing adaptive regulatory frameworks that balance environmental protection, economic feasibility, and social equity in the sustainable transformation of post-coal mining voids.

Post-coal mining voids pose long-term environmental risks, including acid mine drainage formation, heavy metal mobilization, and hydrological instability. These risks are particularly pronounced in tropical regions, where high rainfall accelerates geochemical reactions and contaminant transport processes.

5. CONCLUSION AND RECOMMENDATIONS

Open-pit coal mining generates substantial environmental legacies, particularly land degradation and the formation of post-mining voids that pose long-term risks related to water quality deterioration, geotechnical instability, and ecosystem disruption. This review demonstrates that unmanaged voids can become persistent environmental liabilities; however, when approached through integrated and science-based strategies, they can be transformed into productive assets. Among the most promising pathways is the utilization of water-filled voids for floating photovoltaic (FPV) systems, which simultaneously address clean energy generation, land-use efficiency, and climate mitigation objectives. Such approaches align strongly with the Sustainable Development Goals, particularly SDG 7, SDG 9, and SDG 13, while offering additional socio-economic co-benefits for post-mining communities.

Beyond energy applications, post-coal mining voids exhibit significant potential to support ecological restoration, biodiversity enhancement, water resource management, and socio-economic revitalization. The integration of renewable energy development with ecosystem-based rehabilitation, ecotourism, and community-oriented land uses enables a multifunctional post-mining landscape that contributes to SDG 6, SDG 8, SDG 11, SDG 12, and SDG 15. The adoption of Environmental, Social, and Governance (ESG) principles is crucial in ensuring that void utilization projects are inclusive, transparent, and environmentally responsible. Such frameworks can help balance economic feasibility with long-term environmental stewardship and social equity.

Nevertheless, realizing this potential requires addressing multidimensional challenges related to technical feasibility, environmental safety, economic viability, and regulatory coherence. This study recommends strengthening post-mining governance through integrated policy frameworks, cross-sector collaboration, and phased implementation roadmaps supported by digital technologies such as GIS, 3D modelling, and IoT-based monitoring systems. Governments, industry, and academia must work synergistically to improve regulatory clarity, mobilize sustainable financing, and promote innovation tailored to site-specific conditions. By doing so, post-mining void management can serve as a replicable best-practice model for developing countries seeking to achieve a holistic, inclusive, and low-carbon transition toward sustainable development.

This review advances the scientific discourse on post-coal mining voids by consolidating fragmented research streams into a structured sustainability framework. It underscores the necessity of integrating environmental science, engineering innovation, renewable energy systems, and governance reform in managing pit lakes. By reframing post-mining voids as strategic assets within the sustainability transition agenda, this study contributes to bridging the gap between environmental risk mitigation and sustainable land-use transformation.

Overall, this review reinforces the urgency of transforming post-coal mining voids from environmental liabilities into strategic sustainability assets. By integrating multidisciplinary evidence on environmental risks, renewable energy applications, ecological restoration strategies, and governance mechanisms, this study provides a comprehensive knowledge base to support evidence-based policy formulation and sustainable land-use planning. The synthesis offered in this paper contributes to bridging environmental remediation practices with broader sustainability transitions, particularly in coal-dependent economies undergoing energy transformation. The findings emphasize that long-term monitoring, regulatory enforcement, and cross-sector collaboration are critical to ensuring that post-mining landscapes evolve toward resilient and productive ecosystems.

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