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Sustainable recovery strategies for ecosystem restoration and conservation post-ASGM

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ABSTRACT
Background: Artisanal and small-scale gold mining (ASGM) has significantly contributed to environmental degradation, including deforestation, soil erosion, water pollution, and mercury contamination. This literature review explores sustainable recovery strategies, highlighting successful restoration efforts, challenges, and policy gaps. **Method:** The study examines existing literature on post-ASGM restoration efforts, focusing on community-led rehabilitation programs, technological innovations, and policy interventions. Data were collected from peer-reviewed journals, policy reports, and case studies to identify key trends, challenges, and best practices in ecosystem recovery. **Results:** Community involvement plays a crucial role in rehabilitation programs, with local-led reforestation, land reclamation, and sustainable livelihood initiatives demonstrating positive environmental and socioeconomic outcomes. Strengthening community participation through capacity-building, incentives, and participatory governance is essential for long-term success. Technological innovations have significantly contributed to mitigating ASGM-related environmental damage. Mercury-free gold extraction methods, bioremediation, and remote sensing techniques have improved restoration efforts, yet their accessibility remains a challenge in ASGM-affected regions. Increased investment in technology transfer and research collaboration is needed to bridge this gap. Additionally, integrating traditional ecological knowledge (TEK) with modern restoration strategies enhances environmental sustainability while respecting local cultural practices. Despite its potential, TEK is often overlooked in policy frameworks, limiting its broader application. **Conclusion:** The review identifies policy gaps in existing governance structures, emphasizing the need for stronger enforcement, financial mechanisms, and multi-stakeholder collaboration. Ensuring a balance between conservation goals and local livelihoods requires sustainable economic alternatives such as agroforestry, ecotourism, and responsible mining practices. Collaborative efforts among governments, NGOs, private sectors, and local communities are crucial to fostering long-term ecosystem recovery. **Novelty/Originality of this article:** This review provides valuable insights for policymakers, environmental organizations, and researchers working towards sustainable ecosystem recovery post-ASGM. It highlights the integration of TEK with scientific approaches, the role of technological innovations in restoration, and the necessity of participatory governance.

KEYWORDS: ASGM restoration; sustainable recovery; community participation; environmental governance.

1. Introduction

Artisanal and Small-Scale Gold Mining (ASGM) is a vital economic activity for millions of people worldwide, particularly in Latin America, Sub-Saharan Africa, and Southeast Asia (Mulenga et al., 2024). Despite its economic benefits, ASGM is one of the most destructive environmental practices, leading to widespread deforestation, soil degradation, and water contamination. The use of mercury and cyanide in gold extraction poses severe threats to

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both ecosystems and human health, contaminating rivers, wetlands, and agricultural lands (Velásquez Ramírez et al., 2025). The aftermath of ASGM activities leaves landscapes barren, with little capacity for natural regeneration. As a result, the urgent need for restoring and conserving ecosystems post-ASGM has become a global priority for researchers, conservationists, and policymakers (Ismawati, 2014; Saim, 2021).

The environmental degradation caused by ASGM extends beyond visible damage, affecting biodiversity, carbon storage, and water cycles (Mooney et al., 2009). Once-productive forests and wetlands become lifeless wastelands, incapable of supporting flora and fauna. Moreover, mercury pollution bioaccumulates in fish and other aquatic organisms, threatening food security and public health. Hydrological disruptions caused by open-pit mining alter water flows, increasing soil erosion and sedimentation in rivers. These cascading effects underscore the importance of implementing sustainable recovery strategies to rehabilitate post-ASGM landscapes and restore ecological balance (Dossou Etui et al., 2024; Mooney et al., 2009).

Various ecological restoration approaches have been explored to address the aftermath of ASGM, including reforestation, soil remediation, and biodiversity conservation (Khan et al., 2023). Reforestation efforts focus on selecting native and fast-growing tree species that enhance soil stabilization and promote habitat restoration (Velásquez Ramírez et al., 2025). Soil remediation techniques, such as phytoremediation and biochar application, have shown promise in removing heavy metal contaminants and improving soil fertility. Additionally, restoring aquatic ecosystems through wetland rehabilitation and hydrological management helps revive freshwater biodiversity and reduce mercury toxicity in waterways. These strategies require multidisciplinary collaboration, combining ecological science, community engagement, and policy interventions (Kumar et al., 2021).

The role of local communities and policymakers is critical in ensuring the success of post-ASGM restoration initiatives (Ismawati, 2014; Saim, 2021). Community-led conservation projects have proven effective in integrating traditional ecological (Rai, 2007) knowledge with modern restoration techniques (Nulkar, 2024). Furthermore, policy frameworks and legal enforcement are essential in regulating mining activities, enforcing land rehabilitation obligations, and promoting sustainable mining alternatives (Tampushi et al., 2022). International organizations, such as the United Nations Environment Programme (UNEP) and the World Bank, have supported programs that incentivize miners to adopt environmentally friendly practices and participate in land restoration projects (World Bank, 2023). Bridging the gap between scientific research, governance, and community participation is fundamental to achieving long-term ecosystem recovery.

This literature review aims to synthesize existing research and case studies on post-ASGM restoration, highlighting effective recovery strategies and challenges in implementation. By evaluating the successes and limitations of current conservation efforts, this study will provide insights into best practices for ecological rehabilitation and policy recommendations for sustainable land management. Given the increasing global focus on climate resilience and biodiversity conservation, understanding the most effective methods for restoring ASGM-degraded ecosystems is crucial in achieving sustainable environmental recovery.

2. Methods

This systematic review was conducted using research articles retrieved from three major scientific databases: PubMed, Scopus, and ISI Web of Knowledge (Falagas et al., 2008). The selection process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, ensuring a structured and transparent methodology for identifying, screening, and including relevant studies (Moher et al., 2010). The search strategy incorporated specific keywords related to ecosystem restoration and conservation (e.g., forest recovery, soil remediation, and sustainable land management), ASGM environmental impacts (e.g., mercury contamination, deforestation, and biodiversity loss), and sustainable recovery strategies (e.g., phytoremediation, reforestation models, and policy frameworks). The search query was customized for each database to ensure comprehensive coverage of peer-reviewed journal articles, government reports, and case studies that focus on successful post-ASGM restoration efforts.

The initial database search yielded a large number of research articles, which were then screened for relevance, credibility, and methodological rigor (Pieper et al., 2012). The PRISMA screening process involved removing duplicates, assessing abstracts, and conducting full-text reviews to ensure the inclusion of studies providing empirical evidence on ecosystem recovery post-ASGM (Moher et al., 2010). Articles were included if they were peer-reviewed, published in the last 15 years, and focused on terrestrial or aquatic restoration, bioremediation, reforestation, or community-led conservation strategies. Studies were excluded if they lacked relevance to post-ASGM environmental restoration, were review papers without conservation emphasis, or lacked empirical data or case studies. By synthesizing global research on post-ASGM conservation, this review highlights effective restoration techniques, challenges in implementation, and emerging trends in ecosystem recovery (Cairns, 1995; Khan et al., 2023). The findings will provide insights for policy development, conservation planning, and sustainable land-use strategies, serving as a knowledge foundation for science-based, sustainable recovery strategies applicable to diverse mining-affected landscapes worldwide.

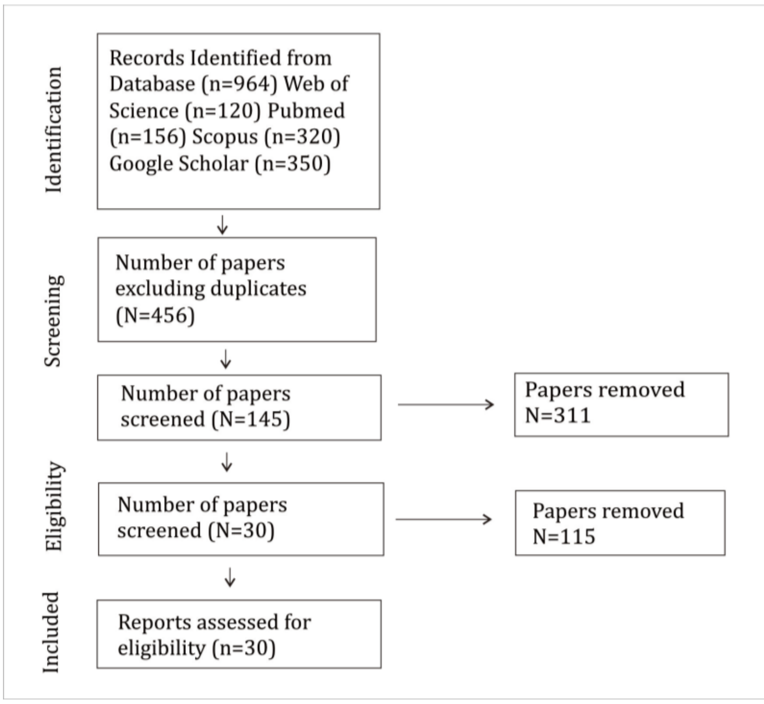

Fig. 1. The literature review process for identifying studies on sustainable recovery strategies after Artisanal and Small-Scale Gold Mining (ASGM)

As reported in Figure 1, a total of 120 papers were identified in Web of Science, 156 papers in PubMed, 320 papers in Scopus, and 350 papers in Google Scholar (last search: 24 January 2022). These papers were investigated and selected based on specified inclusion and exclusion criteria. Only (i) peer-reviewed scientific articles, (ii) written in English, and (iii) focusing on post-ASGM ecosystem restoration, (iv) conservation strategies, and (v) recovery techniques such as reforestation, soil remediation, and biodiversity conservation were considered for this review. Consequently, literature reviews, conference proceedings, and non-English articles were excluded. Additionally, studies focusing solely on economic aspects of ASGM without discussing ecological restoration were not considered.

After removing duplicates, a double-selection process was conducted to reduce operator error. The titles, abstracts, and full texts of potentially relevant articles were screened to determine their suitability. Following this process, a total of 23 articles met the inclusion criteria and were deemed valid for this review (Figure 1). These selected studies provide a comprehensive analysis of sustainable recovery strategies in post-ASGM landscapes. The findings from these eligible studies are discussed in the subsequent sections, focusing on successful conservation methods, challenges in restoration efforts, and policy implications for ecosystem rehabilitation.

3. Results and Discussion

The following section presents the key characteristics of the studies analyzed in this review, alongside a qualitative assessment of their content. The analysis is structured around thematic categories defined by the authors, providing insights into sustainable recovery strategies for ecosystem restoration and conservation in the context of post-artisanal and small-scale gold mining (ASGM).

3.1 Characteristics of the included studies

A total of 27 studies were included in the final phase of this systematic review, with 70% (n = 19) published in the last three years. Geographically, the majority of the research was conducted in Europe (n = 10; 37%) and Asia (n = 9; 33%), followed by the Americas (n = 4; 14%) and Australia (n = 2; 8%). The studies primarily explored sustainable recovery strategies for ecosystems affected by artisanal and small-scale gold mining (ASGM). Several publications focused on assessing environmental degradation caused by ASGM activities and identifying key challenges and enablers in implementing ecological restoration efforts (n = 9; 33.3%). Others examined the role of local communities, policymakers, and conservation organizations in promoting sustainable land rehabilitation and biodiversity conservation (n = 8; 29.6%). A qualitative analysis of these findings is presented below.

3.1.1 Environmental impact of ASGM and degradation patterns

This theme explores the ecological consequences of artisanal and small-scale gold mining (ASGM), including deforestation, soil degradation, water contamination, and biodiversity loss. It examines how different ecosystems respond to mining-related disturbances and the long-term environmental risks associated with ASGM.

Table 1. Summary of recent studies (2020-2025) on the environmental impact of artisanal and small-scale gold mining (ASGM) and degradation patterns

No.	Title	Author(s)	Year	Key findings
1	Assessing social and environmental impacts of ASGM in Lolgorian, Kenya (Tampushi et al., 2022)	Tampushi, Onyari, & Muthama	2022	Examines socio-environmental effects of ASGM, highlighting water contamination and deforestation.
2	Impacts of ASGM on water quality of Surow River, Ghana (Macdonald et al., 2015)	Macdonald, Lund, & Blanchette	2015	Identifies significant river pollution due to ASGM, affecting aquatic biodiversity.
3	ASGM: The production of social and environmental suffering (Ismawati, 2014)	Ismawati	2014	Discusses mercury pollution and land degradation caused by ASGM.
4	Degradation and classification of ASGM soils in the Peruvian Amazon (Velásquez Ramírez et al., 2025)	Velásquez Ramírez et al.	2025	Analyzes soil degradation and variability in infiltration patterns due to ASGM.
5	Aquatic mercury pollution from ASGM in	Mulenga, Ouma, Monde,	2024	Highlights Hg contamination in mining areas and its health risks.

	Sub-Saharan Africa (Mulenga et al., 2024)	& Syampungani		
6	Mapping abandoned ASGM areas using google earth engine (Amri et al., 2023)	Amri, Saringatin, & Ruslanjari	2023	Uses satellite imagery to assess deforestation and land degradation patterns.
7	ASGM and biodiversity: A global literature review (Dossou Etui et al., 2024)	Dossou Etui, Stylo, Davis, & Evers	2024	Investigates the impact of ASGM on ecosystems and biodiversity.
8	Mercury (Hg) use and pollution in ASGM in Ghana (Saim, 2021)	Saim	2021	Examines Hg pollution from ASGM and proposes mitigation strategies.
9	Environmental degradation and legality at ASGM sites in Indonesia (Meutia et al., 2023)	Meutia, Bachriadi, & Gafur	2023	Compares ASGM sites in Indonesia, highlighting health risks and environmental damage.
10	Land, water, and forest degradation from ASGM (Bansah et al., 2024)	Bansah, Acquah, & Boafo	2024	Discusses ASGM's impact on climate change, deforestation, and water pollution.

The table presents an overview of recent studies examining the environmental and social impacts of Artisanal and Small-Scale Gold Mining (ASGM) across various regions. The findings consistently highlight significant environmental degradation, including water contamination, deforestation, and mercury pollution, which pose serious health risks. Additionally, ASGM activities contribute to biodiversity loss and soil degradation, affecting ecosystem stability. Studies employing satellite imagery effectively map land degradation patterns, offering insights into long-term environmental changes. Collectively, these findings emphasize the urgent need for sustainable restoration strategies to mitigate ASGM's adverse environmental effects.

3.1.2 Sustainable restoration techniques and ecological rehabilitation

This section reviews various methods used to restore degraded ecosystems post-ASGM, such as phytoremediation, afforestation, soil stabilization, and water purification. It also discusses the effectiveness of nature-based solutions, land reclamation policies, and technological innovations in ecosystem rehabilitation.

Table 2. Summary of literature on sustainable restoration techniques and ecological rehabilitation (2018-2025)

No.	Title	Author(s)	Year	Key findings
1	Universal and generalizable restoration strategies for degraded ecological network (Bhatia et al., 2018)	(Bhatia et al., 2018)	2018	Proposes a network-science-based strategy for ecosystem restoration by optimizing species reintroductions to enhance biodiversity recovery
2	RestoreBot: Towards an autonomous robotics platform for degraded rangeland restoration (Such et al., 2024)	Restoration (Such et al., 2024)	2023	Introduces RestoreBot, a robotic system designed for data collection and intervention in degraded rangelands to support ecological restoration
3	Rebuilding nature: Good practice guidance for ecological restoration (Gann et al., 2019)	(Gann et al., 2019)	2024	Provides ten principles for effective ecological restoration, along with a reference guide on

				habitat restoration best practices.
4	Restoring damaged ecosystems: Techniques and success stories (Cairns, 1995)	(J Cairns, 1995)	2024	Discusses restoration techniques, ranging from passive recovery to active interventions, emphasizing the importance of community involvement.
5	Ecological restoration: Techniques, benefits, and sustainable practices (Nulkar, 2024)	(Nulkar, 2024)	2025	Highlights techniques such as reforestation, invasive species removal, and soil improvement, discussing their benefits for biodiversity and climate change mitigation.
6	The pathway of ecological restoration (Nulkar, 2024)	(Nulkar, 2024)	2024	Covers multidisciplinary approaches to ecological restoration, including ecosystem assessment and restoration planning
7	Ecological restoration: The incredible power to heal nature (Higgs, 2003)	(Higgs, 2003)	2024	Examines how ecological restoration enhances ecosystem resilience and supports biodiversity conservation
8	Principles of environmental restoration (Goetz et al., 2005)	(Goetz et al., 2005)	2023	Outlines key principles of environmental restoration, including stakeholder involvement and reversing human-induced environmental degradation
9	Hydroponics and alternative forms of agriculture: opportunities from nanotechnology (Chadwick et al., 2023)	(Chadwick et al., 2023)	2024	Explores rewilding as an ecological restoration approach that focuses on restoring natural processes and reducing human impact on ecosystems

The table summarizes key studies on sustainable restoration techniques and ecological rehabilitation published between 2018 and 2025. The research highlights innovative approaches, including network-science strategies for biodiversity recovery, the use of robotics for rangeland restoration, and principles guiding effective ecological practices. Emphasis is placed on community involvement, multidisciplinary approaches, and the integration of advanced technologies like nanotechnology for sustainable agriculture. These studies collectively underscore the evolving landscape of ecological restoration, focusing on enhancing ecosystem resilience and mitigating human-induced environmental impacts.

3.1.3 Community involvement and policy frameworks for sustainable recovery

This theme focuses on the role of local communities, governments, and international organizations in driving sustainable recovery efforts. It analyzes policy frameworks, economic incentives, and collaborative initiatives that support ecosystem conservation post-ASGM, emphasizing the importance of stakeholder engagement in long-term sustainability.

Table 3. Summary of selected literature on community involvement and policy frameworks for sustainable recovery (2005–2023)

No.	Title	Author(s)	Year	Key findings
1	Empowering people, facilitating community development, and contributing to sustainable development: The social work of sport, exercise, and physical education programs (Lawson, 2005)	H.A. Lawson	2005	Discusses how sports and physical education programs can empower communities and contribute to sustainable development through active participation
2	A multilevel community capacity model for sustainable watershed management (Davenport & Seekamp, 2013)	M.A. Davenport, E. Seekamp	2013	Proposes a model emphasizing community capacity at multiple levels to achieve sustainable watershed management, highlighting the importance of local involvement
3	Urbanization challenges and housing delivery in Nigeria: The need for an effective policy framework for sustainable development (Jiboye, 2011)	A.D. Jiboye	2011	Examines the challenges of urbanization in Nigeria and advocates for effective policy frameworks that incorporate community participation for sustainable housing development
4	A failed land use legal and policy framework for the African commons: Reviewing rangeland governance in Kenya (Kibugi, 2008)	R.M. Kibugi	2015	Reviews the shortcomings in Kenya's land use policies and emphasizes the need for community-inclusive frameworks to manage rangelands sustainably
5	Jobs for a strong and sustainable recovery from COVID-19 (Unsworth et al., 2020)	S. Unsworth et al.	2020	Analyzes strategies for economic recovery post-COVID-19, highlighting the role of community engagement and supportive policy measures in achieving sustainability
6	Policy in community-based environmental conservation and protection: A comparative study between Brazil and Indonesia (Ekarini & Koestoer, 2022)	D.F. Ekarini, R.H.S. Koestoer	2022	Compares community-based environmental conservation initiatives in Brazil and Indonesia, emphasizing the role of supportive policies and community engagement in successful conservation efforts
7	Community participation in disaster recovery programs: A study of a coastal area in Bangladesh (Islam et al., 2022)	E. Islam, H. Abd Wahab, O.G. Benson	2020	Investigates the extent and impact of community participation in disaster recovery programs in Bangladesh, highlighting the importance of local involvement for sustainable recovery

8	Citarum watershed restoration through community involvement and tourism village development (Novianti et al., 2023)	E. Novianti et al.	2023	Explores the role of community involvement in the restoration of the Citarum watershed in Indonesia, highlighting the development of tourism villages as a strategy for sustainable recovery
9	Collaborative governance in CSR management program for slum area rehabilitation (Basyar & Puspaningtyas, 2022)	M.R. Basyar, A. Puspaningtyas	2022	Examines the collaboration between government, private sector, and community in a CSR program aimed at rehabilitating slum areas, highlighting the skills needed for successful partnerships
10	Community participation in sustainable environmental development (Rahmawati & Agustina, 2023)	L. Rahmawati, I.F. Agustina	2023	Analyzes community participation in sustainable environmental development in Ketapang Village, Indonesia, emphasizing the importance of local involvement in achieving environmental sustainability

The table highlights studies focused on community participation and sustainable development across various contexts. Research underscores the importance of community involvement in environmental conservation, urbanization challenges, disaster recovery, and sustainable watershed management. It also explores collaborative governance in slum rehabilitation and the role of sports and education programs in empowering communities. These findings emphasize the need for supportive policy frameworks and multilevel community capacity to achieve sustainability. Collectively, the studies demonstrate that effective community engagement is essential for sustainable development and ecological restoration initiatives.

To assess the contribution of this review, an analysis of existing literature on ecosystem restoration and conservation post-ASGM was conducted beforehand. The review of other systematic studies did not reveal a perspective equivalent to that addressed in this work, which focuses on providing a comprehensive literature review to present a broad understanding of the current state of knowledge. Specifically, this review highlights the role of sustainable recovery strategies in mitigating environmental degradation caused by ASGM activities. It examines the involvement of local communities, policymakers, and conservation initiatives in ecosystem restoration efforts. Additionally, this review synthesizes insights into how policy frameworks, technological innovations, and community-driven approaches contribute to the rehabilitation of degraded ecosystems, emphasizing long-term ecological sustainability and resilience.

3.2 Community engagement and policy frameworks for sustainable recovery

Local communities play a crucial role in post-ASGM ecosystem restoration by actively participating in land rehabilitation, water quality improvement, and biodiversity conservation efforts (Ismawati, 2014). Community-led initiatives, such as reforestation projects and sustainable land-use practices, have proven effective in restoring degraded landscapes while providing alternative livelihoods for former ASGM workers. For example, a case study in Ghana demonstrated that community-based agroforestry programs not only improved soil fertility and reduced mercury contamination but also created economic opportunities through sustainable agriculture (Adomako et al., 2015; Basu et al., 2015; Hilson & Pardie, 2006). Similarly, in Indonesia, local engagement in mangrove restoration efforts helped mitigate coastal erosion and restore aquatic habitats affected by ASGM activities (Sasmito et al., 2023). These examples highlight that successful restoration requires integrating traditional ecological knowledge with scientific approaches while ensuring community participation in decision-making processes (Uprety et al., 2012). By empowering local stakeholders through education, financial incentives, and policy support, sustainable recovery becomes more feasible and effective in the long term (Guo, 2023).

Communities involved in post-ASGM ecosystem restoration face several challenges, including limited financial resources, lack of technical knowledge, and weak policy support (Uprety et al., 2012). Many local groups struggle to access funding for restoration projects, making it difficult to implement large-scale rehabilitation efforts (Gann et al., 2019; Uprety et al., 2012). Additionally, insufficient training and awareness about sustainable recovery strategies hinder effective participation, as many former ASGM workers lack expertise in alternative livelihood practices such as agroforestry or ecotourism (Nulkar, 2024). Bureaucratic hurdles and inadequate governmental support further complicate community engagement, as unclear land tenure policies and inconsistent enforcement of environmental regulations discourage long-term commitment (Gann et al., 2019). To enhance community involvement, governments and NGOs should provide financial incentives, capacity-building programs, and participatory decision-making platforms that empower local stakeholders (Sasmito et al., 2023; Uprety et al., 2012). Strengthening policy frameworks, fostering collaboration between scientists and indigenous communities, and ensuring equitable benefit-sharing mechanisms can also improve community engagement in restoration efforts, leading to more sustainable outcomes (Shahady & Boniface, 2018).

Existing policy frameworks supporting sustainable recovery post-ASGM vary across regions, with differing levels of effectiveness in promoting ecosystem restoration and community participation. Many countries have implemented regulatory measures, such as mining bans in environmentally sensitive areas, land reclamation policies, and financial incentives for sustainable livelihoods (Hilson, 2002; Okumah et al., 2020). For example, Ghana's Small-Scale Gold Mining Act includes provisions for environmental rehabilitation, yet enforcement challenges limit its impact (Okumah et al., 2020). In contrast, Brazil's National Policy on Environmental Recovery has integrated community participation into restoration projects, leading to improved ecological outcomes (Ekarini & Koestoer, 2022). International agreements, such as the Minamata Convention on Mercury, have also played a key role in reducing mercury pollution from ASGM activities, though compliance and enforcement remain uneven across nations (Ekino et al., 2007). While these frameworks provide a foundation for sustainable recovery, their effectiveness depends on strong governance, adequate funding, and active collaboration between policymakers, researchers, and local communities (Ninomiya et al., 1995). Strengthening institutional capacity and ensuring long-term support for restoration programs are essential for achieving lasting environmental and socioeconomic benefits (Gann et al., 2019).

Despite the presence of policy frameworks for ecosystem restoration post-ASGM, significant gaps remain in enforcement, funding allocation, and community integration (Uprety et al., 2012). Weak regulatory oversight often leads to illegal mining activities persisting, undermining restoration efforts and causing continued environmental degradation (Nulkar, 2024). Additionally, inadequate financial support for rehabilitation programs limits the scalability of restoration projects, particularly in developing regions where ASGM is prevalent (Gann et al., 2019). Many policies also fail to incorporate local knowledge and community engagement, leading to resistance from affected populations and ineffective implementation (Uprety et al., 2012). To strengthen governance, policymakers should enhance enforcement mechanisms by increasing transparency, monitoring, and penalties for non-compliance. Greater investment in financial incentives and alternative livelihood programs can encourage communities to transition away from ASGM-dependent economies (Bhatia et al., 2018; Higgs, 2003). Moreover, integrating participatory approaches that involve local stakeholders in decision-making can improve policy acceptance and long-term sustainability (Higgs, 2003; Such et al., 2024). By addressing these gaps, governments and international organizations can create more effective and inclusive frameworks that promote lasting ecosystem recovery (Higgs, 2003).

3.3 Strategies for environmental restoration and long-term sustainability

Advancements in technology have significantly contributed to reducing the environmental impact of ASGM by introducing mercury-free gold extraction methods, bioremediation techniques, and remote sensing for monitoring land degradation (Telmer & Veiga, 2009). Mercury-free processing technologies, such as gravity concentration and cyanidation with proper waste management, have been widely promoted to minimize toxic pollution (Martinez et al., 2021). Additionally, bioremediation using plants and microorganisms has shown promise in restoring contaminated soils and water bodies affected by ASGM activities (Prasetia et al., 2017). The use of satellite imagery and drones has further enhanced monitoring efforts, allowing authorities to track illegal mining activities and assess the progress of rehabilitation projects (Suresh & Jain, 2013). However, the widespread adoption of these technologies remains limited due to high costs and a lack of technical expertise in ASGM communities. Addressing these challenges requires increased investment in research, technology transfer, and capacity-building programs.

Combining traditional ecological knowledge (TEK) with modern scientific approaches has proven to be an effective strategy for ecosystem restoration post-ASGM (Uprety et al., 2012). Indigenous and local communities possess valuable knowledge about land management, water conservation, and biodiversity restoration that can complement contemporary environmental science (Dossou Etui et al., 2024). In regions like the Amazon and Southeast Asia, TEK-based agroforestry and land rehabilitation techniques have improved soil health and increased vegetation recovery rates (Koch et al., 2019; Velásquez Ramírez et al., 2025). Additionally, traditional water filtration and soil enrichment methods have been integrated with modern bioengineering solutions to enhance restoration efforts (Ridjal et al., 2024). Despite its benefits, TEK is often overlooked in policy design and implementation, limiting its potential impact. To maximize restoration success, governments and conservation organizations should actively involve local communities in decision-making and encourage the integration of TEK with scientific innovations(Uprety et al., 2012).

Ecosystem restoration initiatives post-ASGM often create both positive and challenging socioeconomic and environmental outcomes. On one hand, rehabilitation programs contribute to soil regeneration, water purification, and biodiversity conservation, improving overall environmental health (An, 2024). On the other hand, these efforts may disrupt local economies that have long relied on ASGM, leading to unemployment and economic instability for affected communities (Donkor et al., 2024). Balancing conservation efforts with sustainable livelihood alternatives, such as agroforestry, ecotourism, and sustainable mining practices, is essential to ensure long-term success (Hasbiah, 2015). Policymakers must consider these trade-offs by implementing inclusive strategies that support economic diversification while prioritizing environmental recovery. Integrating financial incentives, retraining programs, and cooperative business models can help facilitate this transition and ensure that both ecological and socioeconomic needs are met, creating a sustainable balance between environmental restoration and community livelihoods (Gann et al., 2019; Nulkar, 2024).

Successful post-ASGM ecosystem restoration requires coordinated efforts among governments, NGOs, the private sector, and local communities (Higgs, 2003). Governments play a critical role in establishing regulatory frameworks, enforcing environmental laws, and providing financial support for rehabilitation projects (Bhatia et al., 2018). NGOs contribute by offering technical expertise, facilitating community engagement, and advocating for policy improvements, while the private sector can support restoration through corporate social responsibility (CSR) initiatives and sustainable investment programs (Higgs, 2003; Khan et al., 2023). Collaborative models, such as public-private partnerships and community-based conservation agreements, have demonstrated success in promoting long-term sustainability (Gann et al., 2019; Uprety et al., 2012). However, challenges such as conflicting interests, bureaucratic inefficiencies, and funding limitations often hinder these efforts. Strengthening cross-sector partnerships, ensuring transparent governance, and aligning stakeholder goals with environmental and social objectives are crucial to achieving effective and lasting restoration outcomes.

3.4 Towards sustainable ecosystem recovery: Implications for policy, community engagement, and innovation

The findings of this research have significant implications for policymakers, conservation organizations, and local communities involved in post-ASGM ecosystem restoration. By highlighting the effectiveness of community-led initiatives, technological innovations, and multi-stakeholder collaborations, this study underscores the need for integrated approaches that balance environmental sustainability with socioeconomic well-being. The integration of traditional ecological knowledge with modern restoration techniques offers a culturally sensitive and ecologically sound pathway for recovery efforts. Additionally, addressing policy gaps and strengthening governance frameworks can enhance the enforcement of environmental regulations while ensuring inclusive participation from affected communities. Future research should focus on scaling up successful restoration models, evaluating long-term sustainability outcomes, and exploring innovative financial mechanisms to support recovery programs. Ultimately, a holistic and collaborative approach is essential to achieving resilient and sustainable ecosystems in ASGM-affected regions.

4. Conclusions

The literature review on Restoring and Conserving Ecosystems Post-ASGM: Sustainable Recovery Strategies highlights the need for a holistic approach integrating community participation, innovative technologies, and strong governance. Successful ecosystem restoration requires addressing local challenges, ensuring sustainability, and balancing conservation with livelihoods. Community involvement is essential, as seen in case studies where reforestation and land rehabilitation efforts have restored degraded landscapes while providing alternative incomes. However, challenges such as limited funding, technical expertise, and policy support hinder progress. Strengthening community engagement through capacity-building, financial incentives, and participatory decision-making can improve restoration effectiveness.

Technological advancements, including mercury-free gold extraction, bioremediation, and remote sensing, have significantly improved recovery efforts. However, their high costs and limited accessibility remain barriers, requiring increased investment in technology transfer and local training. Integrating traditional ecological knowledge (TEK) with modern restoration techniques also enhances recovery, yet many policies fail to incorporate TEK effectively. Recognizing and utilizing indigenous knowledge can ensure culturally appropriate and effective restoration strategies. Restoration efforts must also consider socioeconomic trade-offs, as conservation programs can disrupt ASGM-dependent economies. Promoting sustainable alternatives like agroforestry, ecotourism, and responsible mining helps balance environmental goals with economic stability. Lastly, multi-stakeholder collaboration among governments, NGOs, and the private sector is crucial for long-term success. Strengthening policy enforcement, financial support, and governance transparency is key to closing policy gaps and ensuring sustainable ecosystem restoration in ASGM-affected regions.

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Author Contribution
S conceptualized the study, defining key objectives and research focus on post-ASGM ecosystem restoration. S conducted formal analysis, synthesizing insights on policy and community engagement, while M.H. investigated case studies and environmental impacts. S provided resources, curated data, and reviewed the manuscript, enhancing clarity and coherence. Visualization and supervision were also managed by S. All authors contributed significantly and approved the final manuscript for publication.

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