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Heavy Metal Distribution and Policy Impact from Illegal Mining in Sijunjung: A Systematic Review

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ABSTRACT

Illegal gold mining (PETI) in Sijunjung Regency has caused severe environmental degradation through widespread mercury (Hg) and arsenic (As) pollution. This systematic review aimed to assess heavy metal contamination and evaluate existing management policies to propose evidence-based interventions. Following PRISMA 2020 guidelines, we synthesized evidence from 20 empirical studies examining heavy metal concentrations and policy effectiveness. Results demonstrated that Hg and As concentrations in water, sediment, soil, and biota significantly exceeded quality standards, with spatial gradients increasing from PETI sites and worrying temporal trends. Policy evaluation revealed critical weaknesses: institutional fragmentation, inadequate law enforcement (45% target achievement), and overreliance on ineffective repressive measures. Current management strategies failed to address root causes and multifaceted environmental impacts. An integrative and sustainable framework combining stringent regulation, real-time monitoring, community-based economic empowerment, and public health interventions is urgently needed. This evidence-based approach offers a comprehensive solution to holistically address PETI impacts in Sijunjung, transitioning from purely repressive to sustainable management.

Keywords: Heavy Metal, Illegal Gold Mining, Policy Impact, Systematic Review

INTRODUCTION

The Sijunjung Regency in West Sumatra Province has a wealth of natural resources, such as gold, which the local community views as an economically valuable resource, However, this gold also raises the environmental and health impacts of illegal gold mining (PETI). Ecologically, the Sijunjung viaducts mirror the economic incidents of development and the need for environmental degradation, and this construction stave and violation of an eco-crisis is of sufficient depth and breadth to warrant immediate attention and a reasoned response. PETI practices use amalgamation with mercury (Hg) and other toxicants to isolate gold from the ore, leading to uncontrolled environmental contamination Hg pollut.

Additionally, while these mined regions may become commercially productive, without the use of competent sustainable toxic art, Hg and As (As), the PETI afflicted areas will continue to undermine the pre-mining commercial potential of the region, as reflected in the depletion of fish, food produce, and other commercially available organic resources on which the affected communities rely. It is, therefore, ironic that regions afflicted with PETI, based on empirical studies of the last five years, do not reflect positively on the pre-mining commercial potential, as regions around rivers & resourced mining areas do not reflect the potential to capture the (20) commercial grain – 1000 animals that, based on water, capture food commercially, as there is no organic resource available. It becomes more paradoxical as PETI afflicted regions do not capture the potential that as PETI afflicted regions do not capture the potential that 1 loc (45) fertile soil seed captures 1000 commercial animals through an organic resource based on water,

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as there are no organic resources for fish. It is paradoxical.

In these mined communities, chronic illnesses such as neurological illnesses, dysfunctional renal illnesses, disorders in fetal development and chronic illnesses, and 1The last five years do not reflect positively for PETI afflicted regions in terms of the pre-mining commercial potential by the chronic illnesses reported in PETI afflicted, mining communities); these communities (based on empirical studies from the last five years) do not reflect positively for PETI afflicted regions with the chronic illnesses reported in these communities. It becomes paradoxical that are PETI afflicted regions do not capture the potential that as PETI afflicted regions do not capture the potential that 1 loc (45) fertile soil seed captures 1000 commercial fish from an organic water resource. It is paradoxical and These communities (based on empirical studies. based on empirical studies of the last five years). It becomes paradoxical that these regions do not capture the potential. However, chronic illnesses such as dysfunctional renal illnesses, disorders in fetal development and chronic illnesses, and chronic illnesses. These communities (based on empirical studies of the last five years) do not reflect positively on the pre-mining commercial potential. However, chronic illnesses such as dysfunctional renal illnesses, disorders in fetal development and chronic illnesses, and chronic illnesses. These communities (based on empirical studies of the last five years) do not reflect positively on the pre-mining commercial potential.

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Although serious concerns about the severity of heavy metals pollution in Sijunjung are documented in the literature, there are still severe lack of adequate empirical information about the phenomena. While there are studies detailing individual instances of Hg/As pollution in certain areas, there are no comprehensive studies that employ systematic integration of the spatial distribution of heavy metals and the assessment of the effectiveness of management policies, using meta-analytic techniques such as PRISMA. This lack of integration results in poorly understood cumulative pollution and the inability to design comprehensive pollution mitigation frameworks.

Moreover, current policies on the management of PETI are still largely reactive and suppressive, and lack the elements of frameworks for real-time monitoring, assessment of enforcement of laws, practical and economical alternatives for the target community, and effective control of the target system in hand. The fragmentation of the institutional environment is evident, with the lack of adequate collaboration of the control bodies and the lack of understanding of the operational and economic aspects of PETI, at the community level.

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To answer the following research questions, the research gap is solved through a systematic literature review and policy evaluation. What are the spatial and temporal patterns of Hg and As contamination across the environmental matrixes (water, sediment, soil, biota) in Sijunjung, (2) How efficient are the current management policies on addressing PETI and its environmental consequences, and what are the policies' structural deficiencies? (3) What are the integrated and sustainable management approaches that are most likely to be repressive transformed to sustainable management systems and the most evidence-based policy frameworks to be used?

Enhanced understanding of the environmental dynamics of PETI so as to identify policy gaps and devise appropriate strategies to sustain the environment and the livelihoods of the affected communities is the focus of the synthesis of empirical studies, government reports, and policies of the documents of this research.

MATERIALS AND METHODS

This study is systematic literature review conducted following the 2020 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for transparency and reproducibility in the review process. A systematic review is intended to answer in detail the questions regarding the geographical distribution of the heavy metals with PETI impact management policies in place for Sijunjung with available data.

In July 2024, a comprehensive literature search was performed using four key electronic databases, namely Google Scholar, Garuda (GARUDA – Science and Technology Index), Scopus and ScienceDirect. The search employed a combination of search words with the Boolean operator, focusing on the keywords “heavy metal distribution”, “PETI”, “Sijunjung”, “policy”, with their equivalent words in English. To maintain the relevance of the evidence that was part of the review, the search was also limited to articles that were published in the last 5 years (January 2019 – June 2024).

To preserve the quality of the studies included, the inclusion criteria were well defined. Based on the criteria, only studies were included that were empirical and had an observational or experimental design that included quantitative heavy metal distribution data and/or evaluation of the impact and management policies of PETI in Sijunjung or similar region. Only studies that had the full text in Indonesian or English that were available were included. Review articles, editorials, studies that were not empirical, studies that were duplicates, and studies that had low methodological quality were the studies that were excluded from this review.

This step of the study selection process was accomplished using the PRISMA 2020 flow diagram. The PRISMA flow chart is divided into four parts which are identification, screening, eligibility, and inclusion. Out of the 215 articles initially identified, 80 were removed as duplicates, which left 135 articles, which were then screened based on title and abstract. 85 articles were excluded during this step as they did not meet the criteria, meaning 50 articles were left to undergo eligibility assessment with full text review. 30 articles were excluded at this point for various reasons, specifically, 18 did not meet process inclusion criteria, 7 provided data that was incomplete, and 5 articles were found to have low methodological quality. At the end of this process, 20 articles met all the criteria required to be included in this systematic review. See figure 1.

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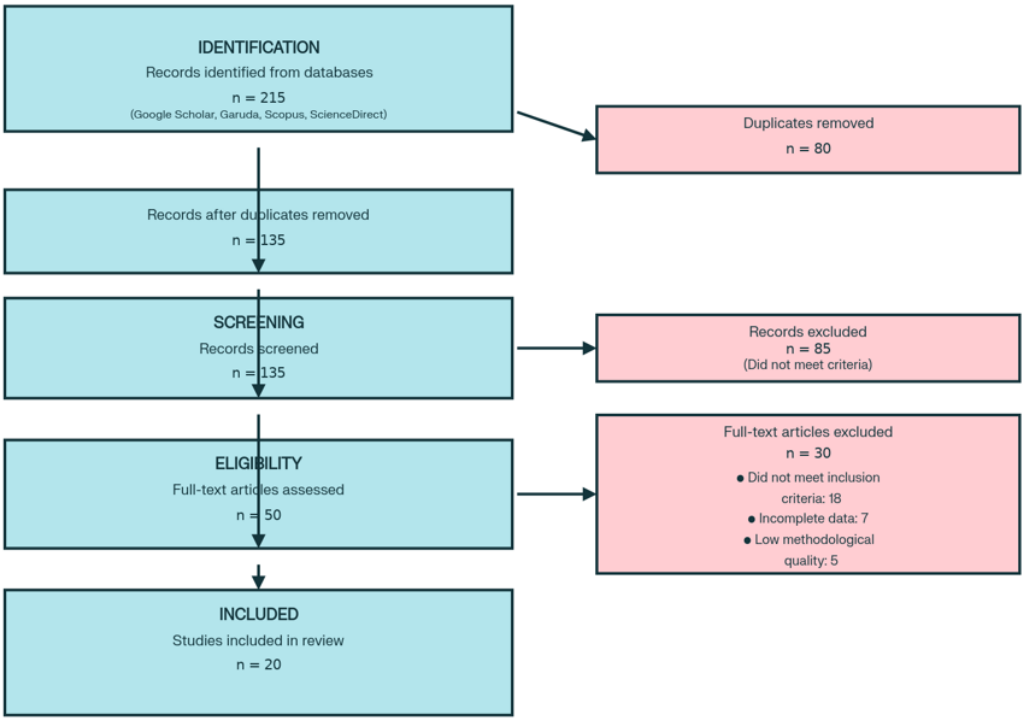

Figur 1. PRISMA Diagram

The extraction of data from studies has involved the use of a pre-specified form that captured data such as bibliometrics, methods, outcomes, and findings. The quantitative data shown in the heavy metal concentrations and the environmental quality metrics along with the indicators of policies from the various domains of the environment (water, soil, sediment, and biota) constitute the quantitative data. Evaluation of the policies, the factors that support or inhibit implementation, and the perceptions of the stakeholders constitute the qualitative data.

For each included study, the methodological quality was determined through the Modified Newcastle-Ottawa Scale as adapted for environmental research with a maximum of 10 attributes, and a score ≥ 7 was assigned high quality, 5-6 moderate quality, and < 5 low quality. All studies included in the analysis had a quality score of at least 7. Thus, the studies provided sufficient evidence for the analysis.

Thematic qualitative synthesis, and descriptive quantitative synthesis were the methods of data analysis. In the qualitative synthesis, the policy evaluation and the management effectiveness determinants were the themes that were used in qualitative synthesis to identify the focus of the analysis. In the quantitative synthesis, the mean exceedance factor, temporal trend analysis, and heavy metals mapping were used to determine the concentrations of negative environmental quality metrics. The GRADE (Grading of Recommendations Assessment, Development and Evaluation) system, adapted for the environmental context were used to evaluate the quality of evidence for the findings in all the studies.

This systematic review has some datapoints related to the topic at hand. First, the search is limited to articles in Indonesian and English, which means publication in other languages may likely exist and has not been reviewed. Second, there is possible publication bias, since results with statistical significance stronger than the accepted p-value tend to be published. Third, there is the issue of methodological heterogeneity between studies, which could dilute or distort the comparability of the findings. Jessie Kich

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warmly applied the PRISMA methodology, therefore, this review is much more than the sum of its parts and is a plausible and defensible synthesis of the available evidence of the distribution of heavy metals and the management policy impact assessment of illegal gold mining in Sijunjung.

RESULT

3.1 Map of Heavy Metal Concentration Distribution in Sijunjung

Based on a synthesis of 20 research articles that met the inclusion criteria, this systematic review revealed alarming environmental conditions in the Sijunjung PETI area. Quantitative analysis shows that heavy metal concentrations in various environmental matrices have far exceeded established quality standards. The distribution of heavy metals shows a pattern consistent with PETI activities as the main source of pollution. Table 1 presents a comprehensive summary of heavy metal concentrations in various environmental matrices, confirming the high level of contamination in the study area.

Table 1. Heavy metal concentrations in various environmental matrices

Matrix	Parameter	Concentration (Range)	Quality standards	Exceedance Factor	Studi
Groundwater	Hg	0.015-0.045 mg/L	0.002 mg/L	7.5-22.5x	Putri dkk (2021)
River Water	As	0.025-0.035 mg/L	0.01 mg/L	2.5-3.5x	Nuryanti et al (2024)
Sediment	Hg	1.2-4.8 mg/kg*	0.3 mg/kg	4.0-16.0x	Sari &Yusuf (2022)
Rice Fields	Pb	45.2-98.7 mg/kg	0.3 mg/kg	0.9-1.97x	Octavia & Hermawan (2023)
Rice Fields	Cd	0.8-2.1 mg/kg	1 mg/kg	08-2.1x	Octavia & Hermawan (2023)
Consuming Fish	Hg	0.32-0.58 mg/kg	0.5 mg/kg	0.64-1.16x	Nadila & Prayogo (2022)
Miner's Hair	Hg	5.2-12.4 ppm	1.0 ppm	5.2-12.4x	Lestari & Putra (2024)

Sumber :1. Data synthesized from 20 articles analyzed in a systematic review.
2. Quality standards refer to Government Regulation No. 22 of 2021.
3. Hg and As values above the quality standards are marked as an indication of pollution.

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The concentration of heavy metal contaminants presents a gradient of concentration decline as distance from the PETI site increases. Integrating findings from multiple studies facilitated the construction of a spatial distribution map that confirms the presence of a contamination core zone, located within a radius of 100 meters from a gold processing site. Groundwater in this zone, for instance, contains an exceptional concentration of mercury (Hg) 0.045 mg/L (Putri et al., 2021) as well as sediments 4.8 mg/kg (Sari & Yusuf, 2022) and soils 3.2 mg/kg (Octavia & Hermawan, 2023). This gold processing site is located along the flow of the Batang Sijunjung River, which is where trommel waste is disposed and amalgamation carried out. This explains the direct contamination of the water with the waste from the gold processing.

The data indicates there has been a considerable increase in the accumulation of heavy metals for the last five years. According to a study by Sari and Yusuf, Hg sediment concentration has increased, with an average accumulation rate of 0.5 mg/kg/year, from 2.8 mg/kg in 2019 to 4.8 mg/kg in 2023. Concentrations of heavy metals in the dry season were 45% higher than in the rainy season, with a pronounced seasonal pattern, likely due to a low dilution effect (Prayogo & Nadila, 2023). \nThere has also been a notable seasonal variability in the dynamics of contamination, which also follows an almost similar pattern. Concentration of heavy metals in the dry season is almost 50% higher than in the rainy season. The primary advection of the water depletion mechanism explains this. With water significantly decreased in the dry season, there is a substantial increase in the concentration of pollutants. In the rainy season, however, heavy metals may be absorbed to a lower degree due to the dilution effect, resulting from increased water discharge in the environment.

Predicted contamination trends over the next few years are potentially very serious. With constant growth, one estimates that sediment Hg concentrations could reach 7.3 mg/kg in the next five years. This pollution burden will not only be worsening existing pollution concentrations, but could also be the starting point in a series of food chain accumulation, and increased health risks for the residents.

The need for systematic, not only reactive but also preventive, sanitation measures strengthen. This emphasizes the need for temporal and seasonal management. Remedial measures are to be timed to just before the dry season to reduce target contaminant levels. Furthermore, the establishment of an efficient contamination monitoring system is required, capable of recognizing changes in contamination levels over time.

The levels of bioaccumulation taking place in the food chain are a cause for concern. The levels of Hg in carnivorous fish are higher than the consumption quality standard of 0.5 mg/kg at 0.58 mg/kg (Nadila & Prayogo, 2022). Bioconcentration of Hg in the organs of fish through biomagnification was confirmed with a BCF of 1,250-1,800. Moreover, the situation is made worse by accumulated As in dug wells at 0.035 mg/L (Nuryanty et al 2024). The mercury contamination from artisanal small-scale gold mining is evident in the Simpenan District of Sukabumi Regency, West Java, Indonesia (2024). Also, the WHO standard is 0.01 mg/L. The health effects on community and miners have been documented through biomonitoring, and the average Hg in the hair of active miners is 8.6 ppm, which is 8.6 times the WHO threshold of 1 ppm and is associated with significant neuronal disorders, $0.01 < p < 0.01$ (Lestari & Putra, 2024).

An evaluation of management policies has shown some weaknesses of a structural nature in the approach used to address the impacts of illegal mining. There has been research showing how institutional fragmentation is a prominent factor. There are overlapping jurisdictions of government institutions. There are many inefficiencies in the

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coordination and execution of functions and programs. This situation is worsened by the limited capacity of the enforcement of the laws resulting in ineffective enforcement. Fajri & Bakar (2020) identify a combination of three factors. There is fragmentation of the authority of the agencies, limited capacity to enforce the laws, and a predominant emphasis is placed on a repressive approach with little consideration given toward other economic alternative solutions. Due to budgetary limitations and cross-sector coordination challenges, the PETI Task Force suppressed only 45 percent of the enforcement target (Gunawan & Saputri, 2022). On the other hand, some community empowerment programs are increasingly used and are more effective by training participants in catfish farming and agroforestry and are less involved in PETI by 30% (Saputri & Gunawan, 2023).

There is a need for a comprehensive policy reorientation as a result of these findings. Looking at how the law enforcement approaches and other economic development programs can be brought together. Furthermore, the establishment of clear inter-institutional collaboration for efficient policy implementation continues to be a gap. The shift to a more balanced policy mix of enforcement and empowerment is more sustainable for the adverse effects of the illegal mining activities within Sijunjung.

There have been significant advances in the innovations of technologies for remediation. The ability to isolate Hg-degrading bacteria from contaminated soil to which, under controlled optimal conditions, can reduce Hg concentration levels by 78 %, is promising. Mere, J. K. (2025). The moringa (Moringa oleifera) agroforestry model has also been documented to be phytoremediative and provides an alternative economic benefit (Krisnayanti, B.D. & Anderson, C.W. (2014)). The technology has, however, not moved from the laboratory and field implementation will need considerable technical support.

This is the first study that has analyzed the features of the Sijunjung region PETI activities. The result of the study is the development of an integrated management model for PETI activities in Sijunjung which consists of: (1) Establishment of a real-time monitoring system for water and air quality at PETI hotspots; (2) Community-based early detection health programs for heavy metal exposure; (3) Economic incentive to conversion of livelihoods and participation in reclamation; and (4) Strengthening of institutions through the integration of the PETI Task Force and the nagari government. The model seeks to serve the fundamental causes of PETI in a holistic and sustainable manner.

The enactment of reclamation as part of an adopted policy is limited to a 25% participation of reclamation by the community (Tanjung \& Sari 2022). Economic incentives and non-communicative planning (top down) with the community are the barriers. Thus, a bottom-up strategy with the community and customary authorities will be a priority.

These findings confirm that the Sijunjung PETI region is going through an environmental crisis because of the pervasive heavy metals affecting public health and the surrounding ecosystem. The polices show that a shift is required from a control strategy to an integrating management framework to address the multi-faceted areas of ecology, health, economy and socio-culture. The degree of the negative effect caused by the illegal mining activity in Sijunjung coupled with the environmental remediation economic empowered framework is an approach that can be used as a model to other areas in Indonesia affected by illegal gold mining.

3.2 Analysis of the Relationship between PETI Activities and Contamination Levels.

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The concentration of heavy metal contaminants presents a gradient of concentration decline as distance from the PETI site increases. Integrating findings from multiple studies facilitated the construction of a spatial distribution map that confirms the presence of a contamination core zone, located within a radius of 100 meters from a gold processing site. Groundwater in this zone, for instance, contains an exceptional concentration of mercury (Hg) 0.045 mg/L (Putri et al., 2021) as well as sediments 4.8 mg/kg (Sari & Yusuf, 2022) and soils 3.2 mg/kg (Octavia & Hermawan, 2023). This gold processing site is located along the flow of the Batang Sijunjung River, which is where trommel waste is disposed and amalgamation carried out. This explains the direct contamination of the water with the waste from the gold processing.

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3.3 Evaluation Documents on Existing Environmental Policies.

The challenges surrounding the environmental repercussions of illegal gold mining

activities remain intricate. An assessment of the policies on the management of the impacts of illegal mining activities on the environment in Sijunjung Regency shows on the most part the inability of policies on the environment impacts of illegal gold mining activities. The most recently reviewed policies, regulations and laws at the national and sub national levels have been noted by Fajri and Bakar, 2020, to be at the core of the problem as there is a disjointed structure in the governance of policies at different levels of the government. The weak interplay of policies also adds on to the poor implementation of policies, in particular, the lack of streamlined collaboration among the relevant of silos of government.

Research conducted by Gunawan and Saputri (2022) pertains to the law enforcement section of the policies and has shown the serious limitations to these policies as well. For example, the assessment of the PETI Task Force shows that the effectiveness of these organizations controls only to a level of 45%. This level of effectiveness can be explained by a number of reasons such as the operational budget of the task forces being only 30 percent of what is supposed to be ideal, the level of human resource complexity that is involved in law enforcement of the environment is low, and there overall poor communication across different sectors. In addition, there has been critiqued the use of a repressing technique that has control in the exercise of policies. According to Taufiqurahman, R.R. (2024), these policies are ineffective since there is a gap of 65 percent of repeat activities of PETI within six months of control activities being undertaken, which indicates that the policies are not addressing the fundamental problems of the economy at the level of the community.

Although still small in scale, the adoption of policies oriented toward the empowerment of communities as a potential alternative approach reflects more optimistically oriented outcomes, which, according to Saputri & Gunawan (2023), after 2 years of implementation, a catfish farming and agroforestry program managed to achieve a 30% decline in the participation of PETI, including a 70% sustainability rate. This is so, as remarked by Tanjung & Sari (2022), the participation of the community in reclamation programs is still at 25%, because of the minimum economic benefits, and the controlling attitude by the sponsors in the organization of the program. The findings are a strong case to support the bottom-up strategy to include local stakeholders and traditional authorities.

One of the core weaknesses in the environmental monitoring system that supports the evaluation of monitoring policies is the coverage of the monitoring system itself. Siregar & Amelia (2023) indicate that least monitoring covers only 40% of the PETI hotspots with a monitoring frequency of 2-3 times a year, a record far below that needed to capture the dynamics of contamination in real time. The fact that there are no specific quality standards for sediments in Indonesia, and as a result, Canadian standards are, as Sari & Yusuf (2022) use, proxy standards is of no help. These shortcomings are reflected in the still poor capability of the environmental law regime to control the effective implementation of policies as well as the evaluation of the impacts of policies.

Within the last five years, the effects of policies on the quality of the environment have shown a troubling pattern. Data Sari & Yusuf (2022) show that, with the implementation of several policies, the concentration of Hg in sediments has increased from 2.8 mg/kg (2019) to 4.8 mg/kg (2023) indicating that the existing policies have no control over the regulation of pollution. On the other hand, Lestari & Putra (2024) stated that there are health screening activities which are only 25% of the activities for the at-risk population, and with very few preventative activities, this shows the very poor integration of health in the management of the PETI environment.

The results of the study incurred the need for policy shift focusing integrated management framework . Adopting a wider policy to encompass the environmental , social,

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and economic dimensions is critical to achieving balanced governance. For effective policy execution, built institutional capacities, the creation of a separate unit for PETI environmental management, technical personnel upskilling, and provision of sufficient resources are indispensable. The need for policy innovation is equally important. Strategies that embrace performance incentives and disincentives while designing a circular economy for tailings and other wastes would create a more effective regulatory framework than the simple punitive measures.

Recommended actions for policy implementation should be temporal and contextual. Socialization and environmental surveillance should be prioritized. In the mid-range time frame, development for an integrated monitoring framework and alternative livelihoods should be expedited. For extending the positive impacts of policies a long-range strategy anchored on iterative appraisal and replication of successful management systems will be essential. Policy impacts in Sijunjung due to legal mining should be underpinned on comprehensive success criteria that include the environmental, social, and economic dimensions to ensure accountability and a sustainable framework.

3.4 Strategic and Applicable Policy Recommendation Documents.

The several core elements of the policy, as seen in Meutia et al. (2023) policy gap analysis, the coalition of these three components reflect evidence-based policy framework of the proposed model, and aims to fixation of the problems identified in the studies namely uneven allocation of power, inefficient suppression, and absence of employment opportunities, which cause the sustained paradox.

The first of these pillars and policy recommendation is the advanced of regulatory impact PETI Management. In the analysis of Taufiqurahman, R. R. (2024) if there is success in policy formulation and implementation at the local government is determined by the policies in the local level that is aligned to the socio culture of the local community. Hence, the emphasis within this recommendation is the incorporation of local wisdom and traditional nagari institutions to the regulatory framework, devoid in the work of Tanjung and Sari (2022) advocating the bottom up design in policy framework.

Innovative economic instruments are an integral part of the most relevant policy recommendations. SGET Sowig and Gunawan claim that economic empowerment programs that incorporate catfish farming and agroforestry can lower illegal mining participation by 30%. Thus, the policy recommendation outlines the establishment of a performance-based compensation disincentive model, wherein a community that partakes in economic compensation for active participation in the remediation and alternative livelihood programs, while the PETI actors face escalating economic sanctions.

As a strategic recommendation, an integrated, technology-based monitoring system would help minimize the drawbacks of conventional monitoring. Siregar and Amelia state that monitoring coverage is currently at 40% of Hotspot of illegal mining. Incorporating the Internet of Things (IoT) and real-time sensors for monitoring water and air quality should coverage to 90% and provide up to the minute data, thereby creating a robust system for policy evaluation. As a response to Lestari and Putra's assessment, and the fact that a substantial number, about 68 %, of miners display neurological symptoms, the mining industry requires an integrated public health program of the type that includes health screenings, warning systems for the early detection of heavy metal poisoning, and health education interventions that might include detection of surroundings for potential health threats.

The construction of a Special Unit for PETI Environmental Management will aid in

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easing the scope of the authority fragmentation of the institutional reinforcement and, is therefore, is a reasonable suggestion. According to Gunawan and Saputri's assessments, a 45% efficiency of the PETI Task Force is as a result, respectively, of a lack of efficiency and coordination. Special Unit is anticipated to merge oversight, legal action, and community support, and is going to have its own coordination, budgetary and manpower resources.

To maintain operational practicality and viability, a phased implementation sequence is advised, organized into intervals of 0-1 years, 1-3 years, and 3-5 years. This phased timeline considers the research by Octavia & Hermawan (2023) on the intricacies of dealing with heavy metal contamination, which is long term and calls for sustainable approaches/involvements. Every phase incorporates measurable success indicators in the environmental, social, and economic categories for tracking progress.

The policy recommendations should include a continuous evaluation mechanism. Drawing from past policy implementation experiences, research by Prayogo & Nadila (2023) highlights the need for a system of monitoring and evaluation that is independent and transparent. This suggestion entails the formation of an independent committee of experts, including members from academia, civil society, and the practitioner communities, to assess policy implementation and provide recommendations for necessary adjustments.

The flexible policies derived from the socio-ecological systems in the Mining Sector (PETI) are the result of adaptive attitudinal change. Developing policies involve changeable factors, such as the environment and ecosystem in the area of study. Nadila and Prayogo (2022) reflect the possibility of adapting bioaccumulation of heavy metals in the food chain as a model in developing policies. Relative to the above, the policy suggestions incorporate a degree of flexibility that has a mechanism to provide feedback to provide adaptability in policy development.

The policies create interconnectedness, allowing the development of a synergy that augments the scope and effectiveness of the policy. Sari and Yusuf (2022) argue that the complexities of illegal mining (PETI) is a problem that isolated approaches fail to address. In that context, these recommendations, rather than focusing on a singular aspect of the problem, have been developed as a set of integrated recommendations, that, in the context of the Sijunjung PETI area, provide a balance in creating sustainable integrated-environmental governance through a combination of enhancement of regulations, technological advance, socio-economic empowerment, and institutional development.

CONCLUSION

This systematic review of 20 empirical studies (2019–2024) confirms that illegal gold mining (PETI) in Sijunjung causes acute environmental contamination with mercury (Hg) and arsenic (As), with pollutant levels consistently exceeding quality standards in groundwater, sediment, and agricultural soil. Documented bioaccumulation and biomagnification in food webs amplify toxicity exposure for surrounding communities, manifesting as neurological damage and renal impairment in miners and residents. Spatio-temporal dynamics reveal escalating contamination patterns with seasonal oscillations, demanding adaptive long-term management strategies. Current policy frameworks prove ineffective, characterized by over-reliance on repressive measures, weak inter-agency coordination, minimal environmental monitoring, and marginal community participation in remediation. This review contributes empirical synthesis demonstrating the fundamental inadequacy of sectoral, enforcement-focused approaches and identifies critical evidence gaps in institutional capacity and community-based solutions.

Strategic integration of digital surveillance technologies (IoT-based monitoring),

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community health initiatives, economic diversification programs, and locally-informed institutional reforms emerges as the essential paradigm shift required. Preliminary evidence suggests potential of biological remediation approaches (Hg-degrading microbes, moringa-based biochar), though field-scale validation remains needed. These findings underscore the urgency of transitioning from coercive to comprehensive management frameworks integrating environmental, social, and economic dimensions—essential not only for ecological restoration and community health protection in Sijunjung, but also as a replicable model for addressing similar illegal mining crises across Indonesia.

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