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Print ISSN: [3006-2497](#) Online ISSN: [3006-2500](#)Platform & Workflow by: [Open Journal Systems](#)<https://doi.org/10.5281/zenodo.23233143>**Sustainability across the Mine Life Cycle in Pakistan: Current Knowledge and Research Priorities****Tehreem Fatima***

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Abstract

Mineral development can support sustainable development only when environmental protection, economic value, social well-being, and sound governance are managed together across the whole life of a mine. Pakistan illustrates the challenge since it produces a range of industrial minerals and fuels and is developing a world-scale copper-gold deposit yet mining remains a small part of the national economy. This purposive integrative review examines how far recent literature supports a sustainable mining transition in Pakistan and where the evidence is missing. Pakistan-specific studies were coded by sustainability dimension and mine life-cycle stage. Most concern the extraction stage and none in the corpus addresses pre-mining baselines or mine closure the stages that determine long-term environmental and social liability. Existing studies document water and soil contamination forest loss and occupational fatalities at individual sites while value addition community outcomes digital technology and recent legal reforms remain little examined. The paper proposes a way of tracing how sustainability commitments are lost between law and practice, and a life-cycle governance framework with a small set of lease-level indicators aligned with the Sustainable Development Goals. Research priorities are set out for each gap.

Keywords:

Sustainability; Sustainable Mining; Pakistan; Mine Life-Cycle; Occupational Safety; Mineral Governance; Mine Closure; Sustainable Development Goals

1. Introduction**1.1. Background**

The supply of minerals has come back to the realm of development coverage. Low carbon energy systems rely on copper, lithium, nickel, cobalt and rare earth elements (REEs) (IEA, 2021), and the International Energy Agency's latest energy outlook shows that the existing pipeline of copper mines will leave room for a 30% shortfall in supply

by 2035 (IEA, 2025). The scenario modelling suggests that the demand for minerals for electricity and transport would require to increase by several times by 2050 (Watari et al., 2019). The same body of work cautions about where and how the new supply is going to be produced. Lèbre et al. (2020) found that 84% of platinum resources and 70% of cobalt resources lie in high-risk contexts, Northey et al. (2017) assessed the exposure of base metal resources to water scarcity and climate change, and Sovacool et al. (2020) called for policy coordination across global mineral supply chains. It is unclear whether the areas where the extraction is taking place will be a part of a just transition (Bainton et al., 2021). In order to use minerals for sustainable development, Ali et al. (2017) contended that there must be resource governance. Further evidence has sustained that argument. Some 10% of the 1,743 tailing facilities disclosed by companies to investors were reported as having significant stability concerns, and a large area of the global footprint of the mining industry is on or near the lands of Indigenous and peasant peoples (Franks et al., 2021; Maus et al., 2022; Owen et al., 2023).

At the beginning of this period, Pakistan has a large potential and small realized output. Coal, limestone, gypsum, rock salt, marble, dolomite, chromite, iron ore, barytes, magnesite and soapstone are the minerals that are recorded in the official statistics for extraction (Finance Division, 2025). In fiscal year 2024 (FY24), mining and quarrying accounted for 1.5% of Gross Domestic Product (GDP) (U.S. Geological Survey, n.d.). It decreased by 4.0% in that year and by another 3.4% in fiscal year 2025 (Finance Division 2025). In this context, the Reko Diq copper-gold project in Chagai, Balochistan, is a step change. The project is expected to have a mine life of not less than 37 years (Barradas, 2025). The sustainability of practice throughout the sector is the subject of this review, and whether this project and the numerous small projects in other parts of the country leave a lasting effect will depend on this.

1.2. Problem Statement

The outline diagnosis is agreed by the existing literature. The reasons for the mineral sector's relatively weak contribution to national income as cited by Jiskani et al (2019) are unregulated practices, weak organization, ineffective implementation of law, lack of capital and technological gaps. Jiskani et al. (2020) have used the fuzzy synthetic evaluation to determine the risks that are affecting the sustainable mining in Pakistan. Khan et al. (2024) examined the governance of mineral resources in relation to sustainability and discussed the problems and reforms faced by it. Ashraf and Cawood (2019) outlined a plan for the implementation of a new mineral policy development framework and a mining cadastre system, which an effective mineral administration must have.

The literature is lacking in information of where the evidence is at and where it is not. Specific wells or locations with documented contamination or fatal accidents are reported as individual studies. Weaknesses in institutions are general, as described in policy papers. There was no review identified that is nationally representative and maps every stage of the mine life cycle, nor was there any review that accounts for the changes in the legislation in 2025. If such a map does not exist, research funding and regulatory scrutiny are driven by what is visible, rather than by what is liable, and closure and pre-mining baselines – which are elements of long-term liability, may simply be overlooked because they have not been studied.

1.3. Review Aim, Questions and Contribution

This review seeks to evaluate the current understanding of sustainable mining from exploration to closure in Pakistan, determine its gaps in knowledge for decision making and link every gap to a particular research avenue. The work is organized by four questions:

- RQ1. What does the recent literature establish about the environmental, economic, social and technological performance of mining in Pakistan?
- RQ2. How is that evidence distributed across sustainability dimensions and life-cycle stages?
- RQ3. Through which mechanisms do formal policy commitments fail to reach mine sites?

- RQ4. What framework, indicators and research agenda follow from the answers to RQ1 to RQ3?

The paper has four contributions. It contains an evidence-gap map of mining sustainability research in Pakistan by dimension and by life-cycle stage. It captures the sometimes-quoted "implementation gap" for which it provides a four-step identification of losses between statute and outcome. It suggests the Life-Cycle Integrated Sustainability Governance (LISG) framework and a Minimum Sustainability Indicator Set that is small enough to be reported by a provincial inspectorate on each lease. It connects eight evidence gaps with research directions and the method and time frame used to achieve them.

1.4. Review Approach

The study is purposive literature review that is integrative, and the study process is presented in Figure 1. Snyder (2019) outlines the methodology of literature reviews and what the standards for them are, and in the light of those standards this review work proceeded.

There were three rounds of sources collected. The first started with the 24 citations that appeared in an earlier draft of this paper and included 19 and eliminated 5 that were weak and/or had no stable source. It was extended using web searching with the term combinations of Pakistan, mining, sustainable, coal, marble, chromite, gemstone, tailings, safety, closure, governance and digital, and backward citation tracking, which identified 38 additional sources and added 57. In the second round, when revising the initial list, 18 sources were introduced for specific parts of the argument, seven sources on existing responsible-mining schemes, three sources on review method and eight sources on the global context. For the third round a review of all factual statements was made with reference to the sources, to which two legal and policy documents from which the text was derived were added to the reference list. There was no search log or screening record maintained in any round and no exact reproduction of the corpus is possible, so the corpus is not a systematic sample and should not be read as such.

All sources were subjected to three conditions. They all had to be journal articles, official statistical or legal publications, or documents from an intergovernmental, standard-setting or professional body, with one trade-press report and one briefing from law firms admitted for facts on Reko Diq and the 2025 legal framework that were not available elsewhere. With three legal and policy instruments that remain effective (Mines Act of 1923, Pakistan Environmental Protection Act of 1997 and National Mineral Policy of 2013), each had to be published in or after 2016. The bibliographic data of all journal articles needed to be verified in the Crossref or OpenAlex registry as well as on the page of the publisher or institutional repository.

The final corpus comprises 77 sources: 61 journal articles and 16 institutions, legal or industry documents. Twenty of the journal articles report evidence or policy analysis specific to Pakistan and form the national evidence base listed in Table 4. Each of these twenty was categorized with respect to one primary sustainability dimension and one primary life-cycle stage, based on its title and abstract, following the rationale of evidence-and-gap maps where the absence of studies becomes visible by mapping them on the matrix of sustainability dimensions and life-cycle stages (Snilstveit et al., 2016). Studies that involved exposure to more than one category were coded according to the medium that was sampled, e.g., dust exposure that is both occupational and environmental was coded to both.

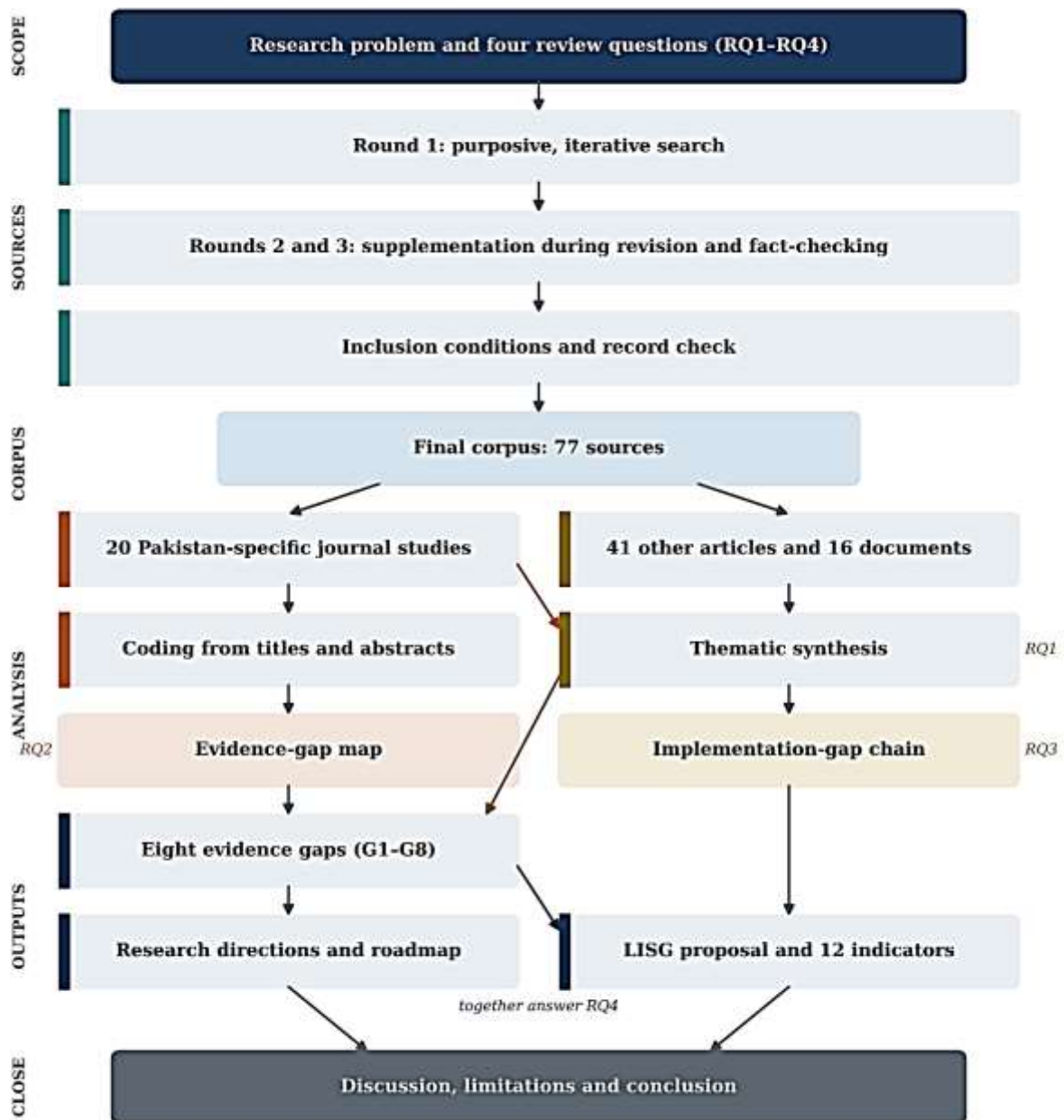


Figure 1. Research flow of the review: source gathering in three rounds, the final corpus, the two analytical tracks and the outputs, with the review question each output answers. Source: authors conceived.

2. Discussion

2.1. Mineral Resources and Mining Context in Pakistan

2.1.1. Mineral Potential

The present studies discussed in this paper have shown the extent and utilization of the minerals in Pakistan. Reko Diq is a locality in Chagai region of Balochistan where copper and gold are found (Barradas, 2025). Coal is also extracted in Balochistan, Surghar Range in Punjab, Makarwal in Punjab and throughout the central Indus Basin with over 160 mines in operation (Jabbar Khan et al., 2020) while lignite is extracted at Thar in Sindh (Nergis et al., 2018). Sultana et al. (2023) conduct a dust study on chromite and coal mines. Marble is being mined in the province of KP, and Buner is said to contribute about 50% of the country's production capacity of Marble (Khan et al., 2019). However, gemstones mining is carried out on a small scale in Gilgit-Baltistan (Lahiri-Dutt & Brown, 2017; Shah et al., 2021) and iron-copper and antimony ores have been tested for beneficiation in Lower Chitral (Anjum et al., 2025).

Table 1 lists the main commodity groups and the sustainability concern of the literature reviewed for each.

Table 1. Principal mineral commodity groups in the reviewed literature and the sustainability concern reported for each.

Commodity group	Locations in the reviewed studies	Sustainability concern reported (source)
Copper–gold	Reko Diq, Chagai, Balochistan	Management of a 45–90 million metric ton per year operation; distribution of revenue and employment (Barradas, 2025)
Coal and lignite	Balochistan; Surghar Range and Makarwal, Punjab; central Indus Basin; Thar, Sindh	Collapse and gas explosions (Shahani et al., 2019, 2021); potentially toxic elements in water and soil (Jabbar Khan et al., 2020; Ahmad et al., 2025; Ali et al., 2023); groundwater discharge (Nergis et al., 2018); health costs (Ayaz et al., 2022)
Marble	Buner, Khyber Pakhtunkhwa	Waste and irregular blocks under conventional mining (Khan et al., 2019); forest loss (Qasim et al., 2026)
Chromite	Mines studied by Sultana et al. (2023)	Heavy metals in mine dust and associated health risk (Sultana et al., 2023)
Limestone, dolomite, gypsum, rock salt	National statistics	Limestone and dolomite extraction rising sharply; gypsum and rock salt falling (Finance Division, 2025)
Gemstones	Gilgit-Baltistan	Informality and customary governance (Lahiri-Dutt & Brown, 2017); unequal livelihood gains (Shah et al., 2021)
Iron–copper and antimony ores	Lower Chitral	Low grades that require beneficiation (Anjum et al., 2025)

Source: compiled by the authors from the studies cited.

2.1.2. Current Mining Practices

There are two production systems. The first would be a few large capital-intensive operations, including the Thar lignite mines (Nergis et al., 2018) and Reko Diq, where initial work started in the first-quarter of 2025 (Barradas, 2025). The second is a greater number of small and medium scale operations, such as coal, dimension stone, limestone, salt, chromite and gemstones, where practices are mostly conventional and technological gaps are large (Jiskani et al., 2019). The conventional method of mining was identified as the least sustainable method among the different methods used in the marble sector in Buner, as it generates the most waste, cracks, and irregular blocks, and semi-mechanized and mechanized cutting were recommended for this sector. In Gilgit-

Baltistan, the informal mining and extraction of gemstones take place according to the principle of collective responsibility (Lahiri-Dutt & Brown 2017).

Recent production numbers illustrate the unevenness in the sector. The rate of extraction of limestone, dolomite and marble increased by 34.1%, 43.3% and 20.2% respectively during the period July to March of fiscal year 2025 as compared to the corresponding period of the previous year, whereas the rate of extraction of coal, natural gas, crude oil, iron ore, gypsum and rock salt decreased in the same period (Figure 2). There is a focus on growth in quarry-type operations.

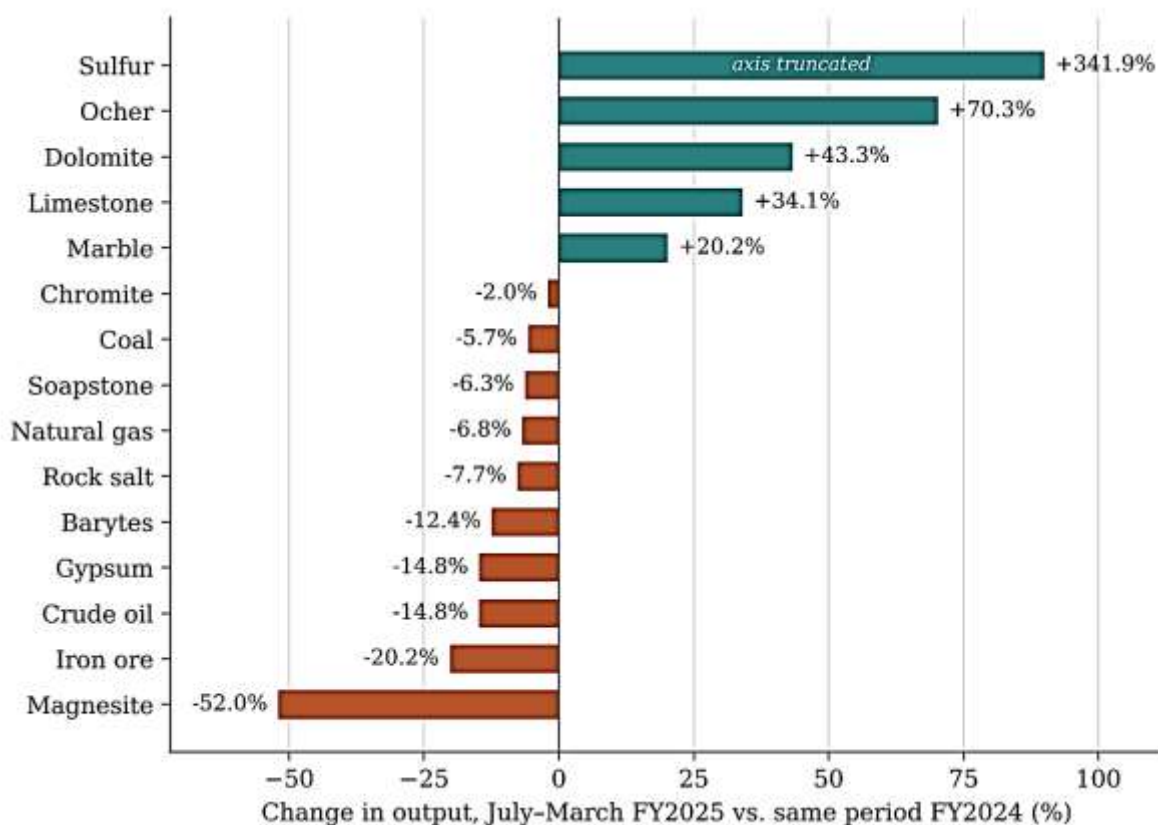


Figure 2. Change in extraction of principal minerals, July–March FY2025 against July–March FY2024, for all fifteen minerals reported. Data: Finance Division (2025)

2.1.3. Sustainability Context

In the context of this paper, sustainability in mining means the ability of a mineral project, and of the mining sector generally, to generate net benefits through the entire life cycle of a mineral project and to not impose uncompensated environmental or social costs on workers, neighbours or future generations. In the minerals sector, there is no single definition that has been agreed upon, but Segura-Salazar and Tavares (2018) have taken a broader look at 25 years of literature and suggested a more comprehensive definition, taking into account trade-offs between the environmental, economic and social aspects. The definition used in this paper was adapted from Gorman and Dzombak (2018), where the life cycle of the mine is shifted to the life cycle of the mineral, and the life cycle approach to sustainable development in mining presented by Asr et al. (2019).

There are two aspects of the national context that make integration across the life cycle challenging. The legal framework also consists of six mineral regulatory frameworks and eight legislative instruments, in addition to thirty-six sets of rules, which are mainly at provincial level and were in place prior to 2025 (Norton Rose Fulbright, 2025). The administrative instruments that underlie the concept of resource governance, a mineral policy development framework and a mining cadastre, are also in the process of being reformed (Ashraf & Cawood, 2019). The following sections will explore each of the sustainability pillars individually, in the context of this background.

2.2. Environmental Dimensions of Sustainable Mining

2.2.1. Mine Waste Management

Mining does much more in the way of material than it sells, and waste rock, coal rejects, quarry waste and, at metal mines, tailings are left behind on the land, unless they are structured to be stable and reusable. Owen et al. (2020) suggested that, around the world, lack of public, timely information on the dangers associated with tailing dams has become normal, and recommended an eight-category screening of disaster risk associated with tailings dams. The Global Industry Standard on Tailings Management now obligates operators to create closure and post closure plans and make information about their facilities public (Global Tailings Review, 2020).

Waste issues documented in Pakistan are of a different nature. Bhatti et al. (2022) compared the drinking-water sources in mining and non-mining areas of Khyber Pakhtunkhwa, and found the mean chromium value to be 497 µg/L in the mining areas and 4.44 µg/L in the non-mining areas, while multivariate analysis showed that both mafic and ultramafic rocks and acid mine drainage were sources. The rock lost during the mining process is the main waste in the dimension-stone industry with the highest loss for conventional mining (Khan et al., 2019). The concentrator could produce up to 90,000,000 metric tons annually (Barradas, 2025) and there was no evidence in the literature of any national precedent for such amounts of tailing and no evidence of any study in the corpus examining the governance of a concentrator of this class in the province.

The same problem is presented in a constructive way in the literature of the circular economy. Kinnunen and Kaksonen (2019) explored the opportunities and constraints for tailings valorization and Tayebi-Khorami et al. (2019) proposed an integrative approach to mining waste that integrated geoenvironmental, geometallurgical, legal and circular-economy aspects to minimize liabilities and maximize value recovery. In the case of Pakistan, the obvious quarry waste for this approach is the waste from the marble industry.

2.2.2. Water Management and Water Pollution

The majority is environmental evidence available across Pakistan is connected to water. Jabbar Khan et al. (2020) reported the presence of potentially toxic elements in the mine water, groundwater, surface water and soil in the central Indus Basin, with the concentration of iron, cadmium, sulfur and copper found to be more than the World Health Organization and national standards for drinking water. Ahmad et al. (2025) conducted the analysis of 22 soil and 134 water samples in Surghar Range, Punjab and determined that iron, zinc and lead were the major toxic elements, the load index of pollution was calculated at 1.20 (moderate level of pollution) and the groundwater was found to be fresh near Indus River and gradually saline towards the west of the range. High concentration of Ni, Cd, Cr, Cu, Zn and Pb were found on 41 soil samples collected from the coal mining sites at Makarwal, which indicates that this area is posing a great risk to humans and environmental systems due to the presence of Cd, Cr and Pb (Ali et al., 2023). Thar Block II: A survey of 58 community wells in 21 villages revealed some discharge of extracted groundwater at a few locations, and substantial accumulation at the Gorano pond (Nergis et al., 2018). Two observations follow. The studies all point to the same direction and the fact that there is contamination from mining in both water and soil is not disputed. However, as per their abstracts, none describes a pre-mining baseline, and none reports on a repeated time series, but each report on a sampling campaign at one location or

region. Because regulators are not aware if contamination is increasing or decreasing, nor do they have an idea of the cost of any remediation, they know that contamination exists. To prevent water management issues, one needs to move towards prevention at the source, treat the water from the mines (which Jabbar Khan et al., 2020, suggest ought to be done explicitly) and keep a monitoring record long enough to show change.

2.2.3. Land Degradation and Biodiversity

Mining impacts the land directly by using pits, dumps and roads and indirectly through settlement and farming opening in the area. Worldwide, Sonter et al. (2020) reported that 16% of the mining areas overlap wilderness, 7% of key biodiversity areas and 8% of mining areas are also protected areas. In the Brazilian Amazon, mining led to the loss of forest cover up to 70 km away from the lease line, more than 12 times the amount of forest loss within leases (Sonter et al., 2017). A pantropical assessment revealed that between 2000 and 2019 3,264 km² was directly lost to industrial mining, while in two thirds of the countries assessed, deforestation was caused indirectly by resource extraction and its infrastructure (Giljum et al., 2022); Bebbington et al. (2018) demonstrated that resource extraction and its infrastructure is a threat to forest cover and community rights.

The best national evidence is provided by Buner which points in the same direction. Within 1988–2018, the area of forests decreased by 97.30 km², of which 4.88 km² were due to direct deforestation caused by marble mining, while 5.69 km² were attributed to the spread of the marble mining area. Within period 1988–2018, 97.30 km² of forest was lost, from which 4.88 km² were attributed to direct deforestation due to marble mining and 5.69 km² were attributed to the area of the marble mining spread. Total forest loss in the district was thus almost twenty times the area lost directly to mining. Because the study does not assign the agricultural and settlement expansion to mining, it is not possible to use the study to quantify the indirect effect, but an environmental assessment limited to the boundaries of the lease would not capture most of the land-use change occurring around the quarries. Assessment at the district or catchment level is required and rehabilitation commitments should be finalized at the planning phase, which allows for the design of pits and dumps to be influenced.

2.2.4. Air Pollution and Emissions

Dust is produced during the drilling, blasting, crushing and haulage activities. The coal and chromite mines were found to be a dust exposure route for workers and the health risk due to heavy metals in fractionated dust from the mines was assessed by Sultana et al. (2023). Barozai and Panezai (2024) also provide a systematic review of the natural hazards of the sector, which also includes gases and dust.

A second, less visible, burden on the atmosphere is greenhouse-gas emissions. For climate change mitigation, transparency of GHG emissions associated with mining is required, Azadi et al. (2020) suggested. There was no published inventory of emissions from the mineral sector in Pakistan available. Particularly, methane is a climate pollutant and also the accumulation of gas, the genesis of the explosions analyzed by Shahani et al. (2019).

2.2.5. Energy and Resource Efficiency

Mining's emissions are primarily associated with energy use. Igogo et al. (2021) examined and identified the opportunities, challenges and enabling approaches for integrating renewable energy (RE) into mining operations, while Jiskani et al. (2021) provided a framework on how to analyse open-pit mines in relation to the goals of green and climate-smart mining. None of the studies in the corpus uses either line of work in relation to a Pakistani mine. The efficiency of the conversion of the in-situ resource into products available to the market (resource efficiency in the narrower sense) is also under-researched. The available evidence relates to the marble, where conventional mining causes the maximum amount of waste (Khan et al., 2019) and to low-grade ores, which can be upgraded by beneficiation (Anjum et al., 2025).

2.3. Economic Dimensions and Resource Efficiency

2.3.1. Contribution to Economic Development

The mining sector's contribution to the national economy is small and is in a downward trend (Finance Division, 2025). Mining is a contributor to development when connected to downstream processing, local procurement, and less when it is restricted to the sale of unprocessed ore and stone, and public revenues are reinvested.

Reko Diq will alter the numbers. The first phase will generate approximately 240,000 metric tons of copper and 297,000 ounces of gold per year, and once expanded, will produce an average of 460,000 metric tons and 520,000 ounces a year, with 50% of the projects owned by the operator, 25% each owned by the province of Balochistan and the federal state entities, respectively (Barradas, 2025). The Pakistan Economic Survey provides rounded estimates of this magnitude: a mine life of over 38 years; in the two phases, 260,000 and 400,000 metric tons of copper; and more than 8,000 jobs (Finance Division, 2025). The level of revenue raises other questions that cannot be answered by the reviewed literature such as the allocation of provincial and federal revenues, defining local content, and the benefits to the host district.

2.3.2. Challenges to Economic Sustainability

The constraints mentioned in the literature are institutional and financial rather than geological. In addition to weak organization and enforcement, insufficient capital allocation and technological gaps are mentioned by Jiskani et al. (2019). The mineral rights policy framework and cadastre as the instrument for administration of mineral rights have needed to be redesigned (Ashraf & Cawood, 2019). Mining projects in developing countries also pose risks to the security of the supply of minerals that were analyzed by Jiskani et al. (2022) using a fuzzy-based method.

2.3.3. Resource Efficiency and Value Addition

The most direct way to increase the value per metric ton mined is through beneficiation. Anjum et al. (2025) reported laboratory results for deposits in Lower Chitral as magnetic separation (90.7 wt.% iron oxide at 65% recovery), froth flotation (average copper content of the concentrates was 5.55 wt.%, and the ore contained less than 0.1 wt.% copper was processed), and stibnite ore was upgraded to 62.0% antimony at 95% recovery. Conventional mining methods in dimension stone are being replaced by semi-mechanized and mechanized methods which helps to reduce waste at source (Khan et al., 2019). In both scenarios there is an indication of technical feasibility, but not economic feasibility. There is no techno-economic or life-cycle assessment of a beneficiation route for a Pakistani ore in the corpus, so policy is moving on before it is based on the evidence to select minerals and locations for processing plants.

2.3.4. Balancing Economic Growth and Sustainability

The economic costs associated with mining on the health and environment are costs even if they do not show up in company accounts. Based on a sample of 150 underground coal miners and a comparison group in Balochistan, Ayaz et al. (2022) determined that underground coal miners are at a higher risk of healthcare costs than other workers, that pollutants like methane and carbon monoxide have an impact on the healthcare costs of the miners, and that the cost of illness increases with narrower seams. These expenses are borne by households and decrease net contribution of the industry.

They are increasingly being called upon by international frameworks. The OECD's responsible mineral supply chains (RMSCs) seek to have companies conduct due diligence on risks involving human-rights violations, conflict, corruption and environmental damage (OECD, n.d.). In a country that aims at investment in copper and other minerals, the environmental and social performance is increasingly a requirement for market access. It is thus

essential to shift from extraction volume to resource efficiency, value addition at home, and the internalization of health and environmental costs for economic sustainability.

2.4. Social Sustainability and Occupational Health and Safety

2.4.1. Occupational Health and Safety

Almost all types of social issues are studied in the context of occupational safety in Pakistani mining. Barozai and Panezai (2024) conducted a systematic review and considered roof falls, gases, dust/ explosions, and insufficient training and neglect of protective equipment as occupational hazards, both natural and human factors. The authors of this study, Shahani et al (2021), analyzed coal-mine accidents over the period of 2010, and found 53 accidents, involving 312 deaths, of which mine collapse was responsible for 36% of the accidents and 51% of the fatalities, while gas explosions caused 19% of the accidents and 17% of the fatalities. A gas explosion fault tree analysis resulted in gas accumulation, gas ignition as the two most important failure modes and the failure modes were associated with 49 out of 53 deaths and 28 out of 35 injuries (Shahani et al., 2019).

The accident record is less than complete. In Punjab, Rehman et al. (2021) identified 377 mining fatalities from 2004 to 2018, noted an increase in fatalities over the years (contrary to the international trend), and highlighted that only fatal or very serious incidents are reported to the regulator, and even then, on an outdated form that does not detail accountability. This is important because the basis of safety management is in leading indicators. The best a regulator can do when learning about hazards is through death is to intervene afterwards.

Chronic disease is not as well covered as accidents. A long-term exposure to gases and dust (Barozai & Panezai, 2024) and to metal-bearing particles (Sultana et al., 2023) is likely to cause sickness over a span of years, and no study in the corpus traces the health of miners over time.

2.4.2. Labor and Social Conditions

The main legislation covering the regulation and inspection of mines is the Mines Act of 1923 (Pakistan Code, 2022). The fact that the same accident types are recurring in above indicates that statutory requirements are not being implemented on the mine site. There is no study of employment relations in Pakistani mines, but workers with informal or insecure employment status are likely to be least able to refuse unsafe work, or to report violations.

There are no studies in the reviewed record that disaggregate employment, income or health impacts by gender.

2.4.3. Community Participation

Mining affects land use, access to water and income distribution. A social license to operate is a concept that conveys that legal authorization is not equivalent to social acceptance. Glückler and Gutiérrez (2025) challenge the managerial interpretation of the concept and the assumption that when there is no conflict, there is a license, and suggest that it should be considered as a social institution that is influenced by the local governance.

This is a point worth keeping in mind in the context of Pakistan as the two studies from the region of Gilgit-Baltistan demonstrate. Lahiri-Dutt and Brown (2017) reported that the informal gemstone mining activity there is regulated by customary collective responsibility rules, which are enforced by customary authorities with legitimacy that they are not outsiders, and suggested that policy needs to start with understanding and respecting the rules. Shah et al. (2021) demonstrated that the impact of artisanal and small-scale mining positively affects household livelihood in the study area with the higher income group benefiting more, however, 85% of members of the community are not concerned with the negative environmental effects of the practice. Small scale mining is then a livelihood and a source of unmanaged harm. Hilson and Maconachie (2020) analysed its connection with Sustainable Development Goals (SDGs) in the case of sub-Saharan Africa.

2.4.4. Stakeholder Engagement

Engagement for a single hearing at the time of environmental approval is not sufficient to meet the standard above. It requires participation at the exploration stage (when access to land is negotiated); at the design stage (when the footprint and water sources are decided); when operating (through grievance systems and made public monitoring); and at closure (when the question is what is the community left with). Bainton and Holcombe (2018) critically examined the social aspects of mine closure while Measham et al. (2024) proposed a research agenda for post-mining transitions, which includes four headings: the definition of post-mining transition in various settings; integration of multiple values in the planning process; the technical-social-economic integration; and the regionalization of the analysis. There is no study in the corpus which discusses either of the topics in the context of Pakistan.

2.5. Technological Innovation for Sustainable Mining

2.5.1. Digital Mining Technologies

Digitalization is an umbrella term for a family of technologies. Barnewold and Lottermoser (2020) identified 107 digital technologies used in the mining industry and concluded that across 158 surface and underground mines, production volume is correlated with uptake of digital technologies with smaller production mines having a lack of digital technologies that are suitable for their scale. Sánchez and Hartlieb (2020) investigated the technological trends in the industry and included a case study on the technical and economic aspects of a disruptive innovation. A recently published systematic review of Mining 4.0 discusses the application of AI, digital twins, autonomous equipment, as well as ore sorting and environmental monitoring via sensors throughout the mining process, and enumerates the barriers to implementation as capital costs, regulation, and skills shortages (Ali et al., 2025). The findings on scale are directly applicable in Pakistan as most of the operations are of small scale.

2.6. Artificial Intelligence and Machine Learning

Jung & Choi (2021) identified 109 papers on machine learning in mining, and most of the papers can be classified under exploration, with the more recent one being published since 2018, and support vector machines being the most popular models used. In Pakistan, which has approximately 50% of recorded coal mine deaths due to collapse, a straightforward application is predicting roof, pillar and goaf instability from monitoring data, to evacuate workers before failure occurs. The continuous sensor gas forecasting would have the same preventive function as provided by Shahani et al. (2019) against accumulation of gas.

2.6.1. GIS and Remote Sensing

The technology that is most readily available to a regulator with limited field capacity is remote sensing. Werner et al. (2019) recently reviewed contributions of GIS and remote sensing to the assessment of mining impacts. Muromba and Xu (2024) used Landsat data collected in 2002, 2007, 2012, 2017 and 2022 to monitor land-use and land-cover change in a mining area in Zimbabwe at 5-year intervals. The same methods are effective in Pakistan, as evident in the Buner study (Qasim et al., 2026). A provincial inspectorate may rely upon them to audit the boundaries of leases, unlicensed workings and rehabilitation at numerous sites.

2.6.2. Technology Adoption Challenges

The conditions, before the technology (capital, skills, a regulator with the capacity to receive and act on data), are a bigger constraint on adoption than the technology itself (Ali et al., 2025; Jiskani et al., 2019). Without these conditions, technology implemented would not be seen as being beneficial on the sustainability front. There is almost no evidence base to answer these questions in the context of Pakistan. The only study in the national corpus that has technology as the main topic is about the extraction method and not digital systems (Khan et al., 2019).

2.7. Policy, Institutional and Regulatory Challenges

2.7.1. Existing Policy and Regulatory Framework

Mines are regulated and inspected under the auspices of the Mines Act, 1923 (Pakistan Code, 2022). The Pakistan Environmental Protection Act of 1997 stipulates that no project can be put into construction or operation until an initial environmental examination, or environmental impact assessment is filed and approved (Government of Pakistan, 1997). The National Mineral Policy 2013 aimed to build a conducive environment for private investment in the sector, to foster stability and attract international investment, to ensure coordination between the Federal and Provincial Government institutions, to ensure environmentally sustainable development of mineral resources and to promote small-scale mining and local private sector participation by the concerned sector (Government of Pakistan 2013). Ashraf and Cawood (2019) came up with an implementation plan for a new mineral policy development framework as well as a mining cadastre system.

2.7.2. The 2025 Reform Wave

There were important changes in the law in 2025. The National Minerals Harmonisation Framework, which was developed by federal and provincial mining departments with international input, is a consolidation of six regulatory frameworks, eight legislative instruments and thirty-six sets of rules, has harmonised royalty rates for ninety minerals and provides an eighteen-month transition period, and is being considered province by province through the development of a Mines and Minerals Act (Norton Rose Fulbright, 2025). The Balochistan Mines and Minerals Act, 2025, was passed and notified on 17th March, 2025; dozens of mineral blocks for small scale mining were auctioned by the Punjab government with electronic bidding and the royalty rates were adjusted; and the royalty rates were rationalised by Khyber Pakhtunkhwa government and few placer-gold blocks were auctioned with electronic bidding system (Finance Division, 2025).

The published description of the framework focuses on investment facilitation, fiscal terms and compliance timelines, and does not include any information on environmental performance, mine closure, financial assurance or community benefit (Norton Rose Fulbright, 2025). At this time, it is unclear whether the reforms will help to close or exacerbate the gap between what is written and what is applied in the areas.

2.7.3. The Implementation-Gap Chain

The challenges faced in the implementation of law rather than the absence of it are identified as the cause of the problem in Pakistan (Jiskani et al., 2019; Rehman et al., 2021). The term "implementation gap" is often not specified..

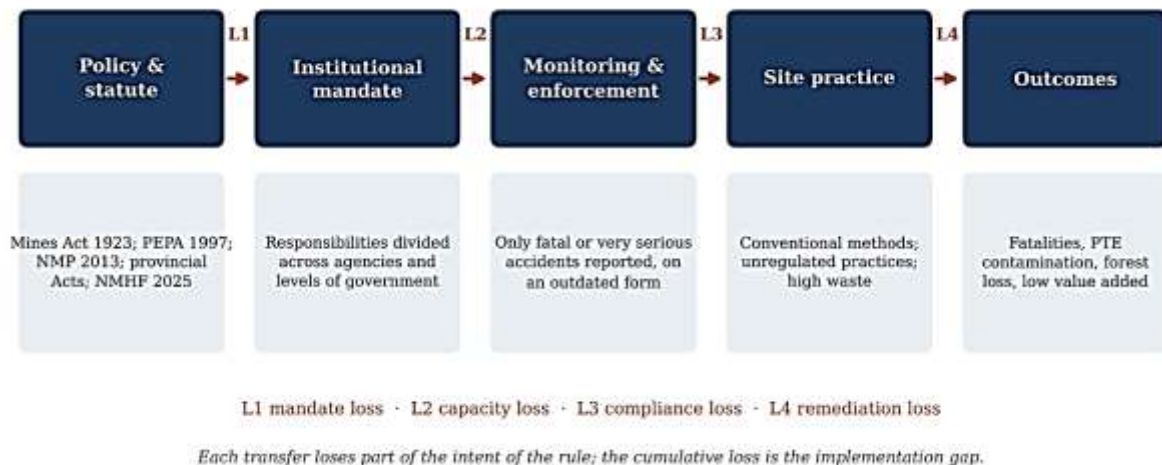


Figure 3. The implementation-gap chain: four losses (L1–L4) between statute and outcome in Pakistan's mining sector. Source: authors conceived synthesis.

The first loss is the one between statute and institution, where responsibilities are shared across agencies and between levels of government, and had already been part of the theme of the 2013 policy (Government of Pakistan, 2013). The second (L2, capacity loss), is when a mandate is handed over to an inspectorate but the tools and data used to enforce the mandate are outdated (Rehman et al., 2021). The third (L3 compliance loss) is between the enforcement and site practice, where the operators carry out conventional practice (Khan et al., 2019) or unregulated practice (Jiskani et al., 2019). The fourth (L4, remediation loss) is when the harm has taken place and not been remedied or compensated through practice.

The remedies are different for each loss – legal harmonization for L1, inspectorate resourcing and remote monitoring for L2, financial extension and technical extension for small operators for L3, and financial assurance and loss closure regulation for L4. The 2025 reforms primarily target L1, as detailed in the source consulted. The evidence is compiled and presented in the context of L2/L3; there is no evidence for L4 since there is no study on closure.

2.8. An Integrated Framework for Sustainable Mining in Pakistan

2.8.1. Why Existing Schemes Do Not Fit the Small-Operator Sector

Before proposing anything new, the question must be asked of whether there is an existing sustainability scheme that may be adopted. There are a number of them that are well developed. The Standard for Responsible Mining of the Initiative for Responsible Mining Assurance covers, among other topics, water, waste, occupational health and safety, Indigenous peoples' rights and closure planning (IRMA, 2018). In the Canadian context, facilities are required to measure their performance every year against what is outlined in the Mining Association of Canada protocols, which cover the areas of tailing, water, biodiversity, climate, safety, community relationships and towards sustainable mining, and the results are independently verified (Mining Association of Canada, n.d.). The Mining Principles of International Council on Mining and Metals (ICMM) established the environmental, social and governance (ESG) standards for the members of the Council, validated at site level (ICMM, n.d.). Tailings facilities are regulated by the Global Industry Standard on Tailings Management closure and post closure (Global Tailings Review, 2020). GRI 14 is a reporting standard that may be used by any mining organisation (GRI, 2024) and the EITI Standard is a measure of transparency and accountability in the oil, gas and mining sector (EITI, 2023).

There are two reviews of such initiatives that are relevant. Sauer and Hiete (2020) examined a sample of 20 multi-stakeholder initiatives for responsible mining and identified many similarities in the roles that they play, their support for conventional mining regulation and their limited impact because they are undertaken by young people. The social impacts of mining were compared with four indicator frameworks by Mancini and Sala (2018) and they concluded that land use and human rights are the greatest negative impacts and employment and income are the greatest benefits, while demographic change and migration are underrepresented. Table 2 puts the schemes in parallel with the context of the mining sector in Pakistan.

Table 2. Existing responsible-mining schemes compared with the conditions of Pakistan's small-operator sector.

Scheme	Type and primary user	Unit assessed	Coverage	Misfit with small operators (authors' assessment)
Standard for Responsible Mining, version 1.0 (IRMA, 2018)	Voluntary standard with independent assessment; mining company	Mine site	Water, waste, safety, Indigenous rights, closure planning; draft revision adds exploration and processing	Presupposes a site management system and an external audit
Towards Sustainable Mining (Mining Association of Canada, n.d.)	Industry-association program; member company, externally verified	Facility	Nine protocol areas for operating facilities	Depends on an association of capable companies
Mining Principles (ICMM, n.d.)	Membership requirement; company members	Company and site	Ten principles across environment, social and governance	Applies only to member companies
Global Industry Standard on Tailings Management (Global Tailings Review, 2020)	Technical standard; operator of a tailings facility	Tailings facility	Full facility life cycle including closure and post-closure	Relevant only where tailings facilities exist
GRI 14: Mining Sector 2024 (GRI, 2024)	Reporting standard; any mining organization	Organization	Sustainability reporting topics	Requires a reporting function; a disclosure standard, not a regulatory minimum
EITI Standard 2023 (EITI, 2023)	Transparency standard for oil, gas and mining	Country and sector	Transparency and accountability of resource management	Not a site-level safety or environmental standard
LISG (this paper)	Proposed regulatory minimum; provincial inspectorate	Lease	Exploration to post-closure	Untested; requires a lease registry

Source: compiled by the authors from the scheme documents cited.

The comparison results in 3 mismatches. The first is about the user. Company facing schemes in Table 2 are carried out by a company who apply them to their own operations and then they are verified by an assurer or industry body. In Pakistan the actor that must apply a standard to a large number of small operations is the provincial inspectorate. The second relates to the unit. The problem of fit to scale is general, as the schemes assess a site,

facility or organisation that has a management system and a reporting function which a small coal mine or family marble quarry cannot be assumed to have (Barnewold & Lottermoser 2020). The third relates to coverage. The findings of this review paper reveal that there are gaps in evidence in Pakistan before the lease and after production. The draft revision of its Standard expands coverage to all stages of mineral development, including exploration, project development and mineral processing (IRMA, 2018), suggesting that even wider life-cycle coverage of the international schemes is being developed.

These schemes continue to be the schemes of choice for Reko Diq and other large schemes, and none of the proposals below replace these schemes. What is missing is a floor under them; a regulatory minimum is needed, that a provincial regulator can administer, and that is to be made to cover the whole life cycle. The framework which follows is intended to be that bottom line.

2.8.2. Structure of the LISG Framework

The Life-Cycle Integrated Sustainability Governance (LISG) guidelines outline for each phase of the mine life cycle the actions to be taken along four pillars (environmental, economic, social and technological) and the way to verify them. It is based on three design principles. The four pillars of integration are implemented concurrently at all stages of the tasks in accordance with the life cycle approach to sustainable development in the mining industry (Asr et al., 2019). In line with the shift from life cycle of the mine to life cycle of the mineral as detailed in Gorman & Dzombak (2018), anticipation is given the same weight as extraction (stage 2) both prior to and after extraction. Verifiability: every task has an indicator that can be verified by a regulator without the operator's testimony.

The framework calls for baseline surveys of water, soil and biodiversity before mining lease is considered, and mapping of customary lands and resource rights, at exploration. It needs an impact assessment on catchment scale, a closure plan with costed rehabilitation and a financial assurance instrument in proportion to the cost of the rehabilitation. It must be monitored for potentially toxic elements, dust and land disturbance, leading safety indicators, and progressive rehabilitation during development, and during extraction. At processing it needs to be resolved that residues shall be characterized for re-use. It needs to be verified by remote sensing and field audit before the assurance is released at closure, in order to ensure rehabilitation; it also demands a plan to rehabilitate the workers and settlements that relied on the mine.

Under the four pillars is a governance core that has four components: harmonized law across provinces; a single data standard used by all inspectorates; an open registry, where indicators at lease level are published; and periodic independent audit. However, the others rely on the registry, as without data, neither enforcement nor research is possible.

2.8.3. Grounds for the Framework

The framework is justified on five arguments, each of which can be examined with content offered in this paper.

Empirical traceability. Each life-cycle task has an associated problem described in the national literature, with the study behind each indicator named in Table 3. Absence of any described pre-mining reference is addressed in the environmental studies by the baseline surveys. This catchment scale assessment addresses the Buner finding that total forest loss was much higher than the direct loss due to mining (Qasim et al., 2026). The fact is only fatal or very serious accidents come to the regulator's attention, leading safety indicators address this issue. In response to the evidence from the Gilgit-Baltistan that customary authorities have the legitimacy that allows them to govern informal mining, recognition of customary rights is a solution (Lahiri-Dutt & Brown, 2017).

Correspondence with the implementation-gap chain. The governance core is exactly equivalent to the four losses. Harmonised law covers mandate loss (L1). Capacity loss (L2) can be addressed through a common data standard and a registry and satellite monitoring, as both allow a small inspectorate to see many sites. This is because compliance loss (L3) will become apparent to the buyer, the lender and neighbors, in addition to the

inspector, and this is what published lease-level indicators will address. Financial assurance can be considered a solution to remediation loss (L4).

Fit to the regulated population. The schemes in Table 2 fit neither with respect to the unit of account nor the user. The two points that the schemes in Table 2 do not fit are the unit of account and the user. The framework establishes the things that have to be measured, and gives the mechanisms of compliance flexibility, depending on the scale.

Parsimony. There are only 12 indicators, which are not too many to measure for each lease. This is a conscious compromise of completeness for coverage.

Compatibility. The indicators address issues of topics that are also addressed in the international schemes, including water, waste, safety, closure and community relations (IRMA, 2018; Mining Association of Canada, n.d.). The framework, therefore, is designed to be under those schemes, and not to be in competition with them. It remains to be seen if an operator under one of them can provide the indicators without extra effort.

The framework is additionally open to refutation. It raises three propositions, which can be tested when the indicator data is available. P1: If the indicators of comparable leases are published, those leases will have lower injury frequencies and higher rehabilitation ratios within 3 years than leases whose indicators are not published. P2: Provinces with an open registry system and satellite verification will identify more unlicensed workings and boundary violations per inspector than provinces where the provinces only do a field inspection. P3: Where financial assurances are for a higher proportion of the estimated closure cost, the area of abandoned, unrehabilitated workings will increase more slowly. These propositions are not met; the framework needs to be changed or scrapped.

2.8.4. Minimum Sustainability Indicator Set

Table 3 presents the 12 indicators (3 per pillar). Three selection criteria were met. All indicators had to address a problem that was reported in the literature examined. They all may be available from a source accessible to the provincial regulator: a water sample (E1), satellite imagery (E2), production and sales returns (E3, C1, C2), accident and health registers kept by the employer (S1, S2), or from a return from the leaseholder (C3, S3, T1 to T3). All had to be linked to an SDG target, with the aim of sector reporting being to support national reporting. The feasibility and cost of collecting each indicator have not been tested.

Table 3. Proposed Minimum Sustainability Indicator Set (MSIS) for lease-level reporting.

Pillar	Indicator	Unit	Problem addressed (source)	SDG target
Environmental	E1. Concentration of potentially toxic elements at the nearest downstream water point relative to baseline	Ratio	Water contamination (Jabbar Khan et al., 2020; Ahmad et al., 2025)	6.3
Environmental	E2. Disturbed land under rehabilitation as a share of all disturbed land	%	Forest and land loss (Qasim et al., 2026)	15.3
Environmental	E3. Waste generated per metric ton of product, and share reused	t/t; %	Quarry waste (Khan et al., 2019)	12.5
Economic	C1. Recovery of the mineable resource	%	Waste and irregular blocks under conventional mining (Khan et al., 2019)	12.2
Economic	C2. Share of output processed domestically beyond crushing	%	Unbeneficiated low-grade ores (Anjum et al., 2025)	9.2

Pillar	Indicator	Unit	Problem addressed (source)	SDG target
Economic	C3. Financial assurance held as a share of estimated closure cost	%	Closure and post-mining transition (Bainton & Holcombe, 2018; Measham et al., 2024)	16.6
Social	S1. Injury frequency rate including non-fatal injuries and near misses	Per million hours	Fatal-only reporting (Rehman et al., 2021)	8.8
Social	S2. Workers under periodic health surveillance	%	Health costs and dust exposure (Ayaz et al., 2022; Sultana et al., 2023)	3.9
Social	S3. Community grievances resolved within 90 days	%	Community disregard of environmental effects; unequal gains (Shah et al., 2021)	16.7
Technological	T1. Underground workings with continuous gas monitoring	%	Gas accumulation and ignition (Shahani et al., 2019)	8.8
Technological	T2. Energy intensity and renewable share of site energy	kWh/t; %	Emissions transparency; renewable integration (Azadi et al., 2020; Igogo et al., 2021)	7.2; 13.2
Technological	T3. Completeness of digital returns to the lease registry	%	Cadastre and information system (Ashraf & Cawood, 2019)	16.10

Source: authors conceived. SDG target numbers refer to the United Nations 2030 Agenda;

2.8.5. Status and Limits of the Proposal

LISG is a proposal that was developed based on a literature review. It has not been used in any lease to date and the indicators have not been field-tested. Three questions are yet to be resolved: what should be the number of the leases in question, and whether they can be supplied with even the simple value of returns that is assumed, and what would be the cost of an inspectorate to run the registry? The next steps involve a process of structuring a consultation with regulators, operators and community members to pilot test the framework content and a pilot phase in a single mining district to gather the indicators over a one-year period. While awaiting that the framework should be understood as a well-reasoned hypothesis on what a workable regulatory minimum might look like.

2.8.6. Alignment with the Sustainable Development Goals

The link between mining and Sustainable Development Goals was explored by Monteiro et al. (2019) and Agusdinata et al. (2023) combined life-cycle sustainability assessment with the Goals to assess the sustainability impacts of critical mineral extraction. The indicator set in Table 3 is mapped to targets under Goals 3, 6, 7, 8, 9, 12, 13, 15 and 16. It is designed to allow the contribution of the mineral sector to the national commitments to be reported based on data that is gathered for regulatory purposes.

3. Research Gaps and Future Directions

3.1. Evidence-Gap Map

Twenty Pakistan specific studies were identified and coded as shown in Table 4, and Figure 4 shows the result in matrix format of sustainability dimension against life-cycle stage.

Table 4. Pakistan-specific studies in the review corpus (n = 20) and their coding by primary dimension and life-cycle stage.

Study	Commodity and location	Dimension	Stage	Principal finding or subject (from abstract or title)
Ahmad et al. (2025)	Coal; Surghar Range, Punjab	Environmental	Extraction	22 soil and 134 water samples; Fe, Zn and Pb the main toxic elements; pollution load index 1.20; salinity rises westward
Ali et al. (2023)	Coal; Makarwal, Punjab	Environmental	Extraction	41 soil samples; high Ni, Cd, Cr, Cu, Zn and Pb; Cd, Cr and Pb pose significant risk
Bhatti et al. (2022)	Mining and non-mining areas; Khyber Pakhtunkhwa	Environmental	Extraction	Mean Cr 497 µg/L in mining areas against 4.44 µg/L elsewhere; sources are mafic-ultramafic rocks and acid mine drainage
Jabbar Khan et al. (2020)	Coal; central Indus Basin	Environmental	Extraction	More than 160 active mines; Fe, Cd, S and Cu exceed drinking-water standards; treatment of mine drainage needed
Nergis et al. (2018)	Lignite; Thar Block II, Sindh	Environmental	Extraction	58 wells in 21 villages surveyed; extracted groundwater discharged at several sites, accumulating at Gorano pond
Qasim et al. (2026)	Marble; Buner	Environmental	Extraction	1988–2018: mining area +5.69 km ² ; 4.88 km ² of forest lost to mining; total forest loss 97.30 km ²
Sultana et al. (2023)	Coal and chromite mines	Environmental	Extraction	Health risk assessment of heavy metals in fractioned mine dust (title; abstract not accessed)
Anjum et al. (2025)	Iron–copper and antimony ores; Lower Chitral	Economic	Processing	Laboratory beneficiation: Fe ₂ O ₃ concentrate 90.7 wt.%; Cu concentrate 5.55 wt.%; Sb 62.0% at 95% recovery
Ayaz et al. (2022)	Coal; Balochistan	Economic	Extraction	150 underground miners; higher healthcare costs than other workers; cost of illness rises as seams narrow
Barozai & Panezai (2024)	All mining; national	Social / OHS	Extraction	Systematic review: roof falls, gases, dust and explosions; insufficient training and neglected protective equipment
Jiskani et al. (2019)	All mining; national	Social / OHS	Extraction	Appraisal of the mine safety crisis: unregulated practices, weak organization and enforcement, capital and technology gaps
Rehman et al. (2021)	Mining; Punjab	Social / OHS	Extraction	377 fatalities in 2004–2018; only fatal or very serious accidents reported; reporting form outdated

Study	Commodity and location	Dimension	Stage	Principal finding or subject (from abstract or title)
Shahani et al. (2019)	Coal; national	Social / OHS	Extraction	Fault-tree analysis of gas explosions: gas accumulation and ignition; 4 of 7 root causes linked to 49 of 53 deaths
Shahani et al. (2021)	Coal; national	Social / OHS	Extraction	53 accidents and 312 deaths; collapse 36% of accidents and 51% of deaths
Lahiri-Dutt & Brown (2017)	Gemstones; Gilgit-Baltistan	Social / OHS	Extraction	Informal mining governed by customary rules of collective responsibility
Shah et al. (2021)	Artisanal and small-scale mining; Gilgit-Baltistan	Social / OHS	Extraction	Positive livelihood effect, larger for high-income households; 85% disregard adverse environmental effects
Khan et al. (2019)	Marble; Buner	Technological	Extraction	Conventional mining least sustainable; semi-mechanized and mechanized methods recommended
Ashraf & Cawood (2019)	All minerals; national	Governance	Planning and licensing	Implementation plan for a mineral policy development framework and mining cadastre system (title)
Khan et al. (2024)	All minerals; national	Governance	Planning and licensing	Evaluation of sustainable mineral resources governance: challenges and reforms (title)
Jiskani et al. (2020)	All mining; national	Governance	Extraction	Fuzzy synthetic evaluation of risks impeding sustainable mining (title)

OHS: occupational health and safety. Coded from titles and abstracts in a single pass. "(title)" marks entries for which no abstract could be accessed.

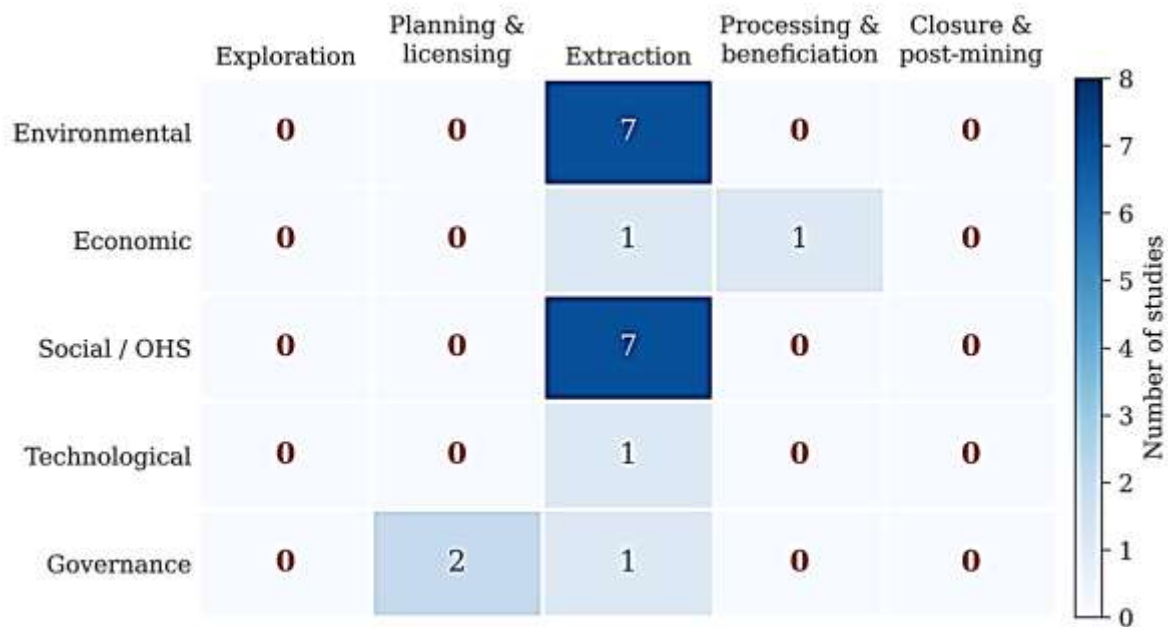


Figure 4. Evidence-gap map of the twenty Pakistan-specific studies reviewed, by primary sustainability dimension and life-cycle stage. Zero cells mark the absence of any study in the corpus.

Distribution is very uneven. 17 studies (85%) cover the extraction stage. Two on addressing planning & licensing, one on processing and none on addressing exploration or closure. Environmental and social or occupational studies both take seven dimensions, governance three, economic two and technological one. There are 25 cells in the matrix, 18 of which are empty; except for the cells in the extraction column, governance is only populated at the planning stage and economics is populated at the processing stage.

This pattern responds to the second review question, as is limited to a purposive corpus. Visible, apparent harm at working mines has been the subject of research. It has not yet come to the point where it is easiest to avoid harm (during exploration and planning) or when it becomes permanent (closure).

3.1.1. From Gaps to Research Directions

The map reveals few gaps, and the thematic review also identifies these gaps. Table 5 maps each with a research direction, the most appropriate methodology for that direction, and the stage of the LISG framework that the knowledge would apply to. The direction is determined by the distance that it fills, and progress is measured by whether the corresponding cell in Figure 4 fills.

Table 5. Linkage between evidence gaps identified in this review and proposed research directions.

Gap	Evidence from this review	Research direction	Principal method	LISG stage served
G1	No study of closure, abandoned mines or post-mining land use in the corpus	Closure-liability inventory; affordable financial assurance; post-mining livelihoods	Remote sensing inventory; cost modeling; household survey	Closure and post-mining
G2	No pre-mining environmental or social baseline described	Standard baseline protocol tested at current exploration projects	Hydro- and geochemical survey; rights mapping	Exploration

Gap	Evidence from this review	Research direction	Principal method	LISG stage served
G3	Seven environmental studies, each a site- or region-specific campaign	Permanent monitoring transects; district-wide land-cover time series	Repeated sampling; satellite time series	Extraction; processing
G4	Safety evidence dominated by fatal-accident counts	Near-miss and exposure reporting standard; miner health follow-up; ground-instability and gas prediction models	Cohort study; sensor data; machine learning	Extraction
G5	Value addition supported only by laboratory beneficiation tests	Techno-economic and life-cycle assessment of processing routes and quarry-waste reuse	Process modeling; life-cycle assessment	Processing
G6	Community evidence from one region; no gender-disaggregated data	Comparative social studies; longitudinal study of social acceptance in Chagai	Mixed-methods panel survey	All stages
G7	One technology study; none on digital systems	Readiness survey; documented small-scale sensing pilots	Survey; field pilot with cost accounting	Development; extraction
G8	2025 legal reforms not evaluated for sustainability outcomes	Before-and-after evaluation across provinces using the MSIS	Comparative policy evaluation	Planning and licensing; governance core

MSIS: Minimum Sustainability Indicator Set (Table 3). Source: authors conceived.

G1 - closure and post-mining. No study in the corpus addresses mine closure, so a provincial closure-liability inventory affordable financial assurance and research on post-mining settlements are needed (Bainton & Holcombe, 2018; Measham et al., 2024). Reuse cannot be assumed: only about one-third of 51 closed Finnish metal mines gained recreational uses and nearly one-third new industrial ones (Kivinen, 2017).

G2 - exploration-stage baselines. No study in the corpus reports pre-mining conditions for a Pakistani deposit so later contamination cannot be attributed. A standard baseline protocol should be tested at current exploration projects in Khuzdar and Punjab (Finance Division, 2025).

G3 - longitudinal and basin-scale environmental evidence. The water and soil studies reviewed are one-off campaigns at specific sites. Permanent monitoring transects and satellite time series should extend the Buner approach (Qasim et al., 2026) to other mining districts.

G4 - safety beyond fatality counts. Safety research rests on records that capture mainly fatal or very serious accidents (Rehman et al., 2021). A reporting protocol for near misses and exposures long-term health follow-up and predictive models of ground instability and gas accumulation are needed.

G5 - economics of value addition and waste valorization. Laboratory beneficiation results should be followed by techno-economic and life-cycle assessments comparing domestic processing with the sale of ore. The same applies to marble quarry waste given the known bottlenecks to valorization (Kinnunen & Kaksonen, 2019).

G6 - communities, gender and small-scale mining. Community evidence is confined to Gilgit-Baltistan, so gender-disaggregated studies are needed in Balochistan, Thar and the marble belt. A longitudinal study in Chagai should begin before Reko Diq's first production in 2028 (Barradas, 2025).

G7 - digital readiness. The corpus contains no evidence on digital or sensing technology in Pakistani mines. A readiness survey and small-scale monitoring pilots would test the scale at which Barnewold and Lottermoser (2020) found solutions lacking.

G8 - evaluation of the 2025 reforms. Province-by-province enactment of the harmonization framework allows a before-and-after evaluation using the indicators in Table 3. It should be designed now, while baseline data can still be collected.

3.1.2. Research Roadmap

The instructions are presented in the directions on three horizons in figure 5. Near term work is work which only requires existing data and modest funding; inventories, protocols, reporting standards and evaluation design. Field infrastructure and pilots are needed for medium term work. Long-term outcomes are institutional, and rely on preceding steps.

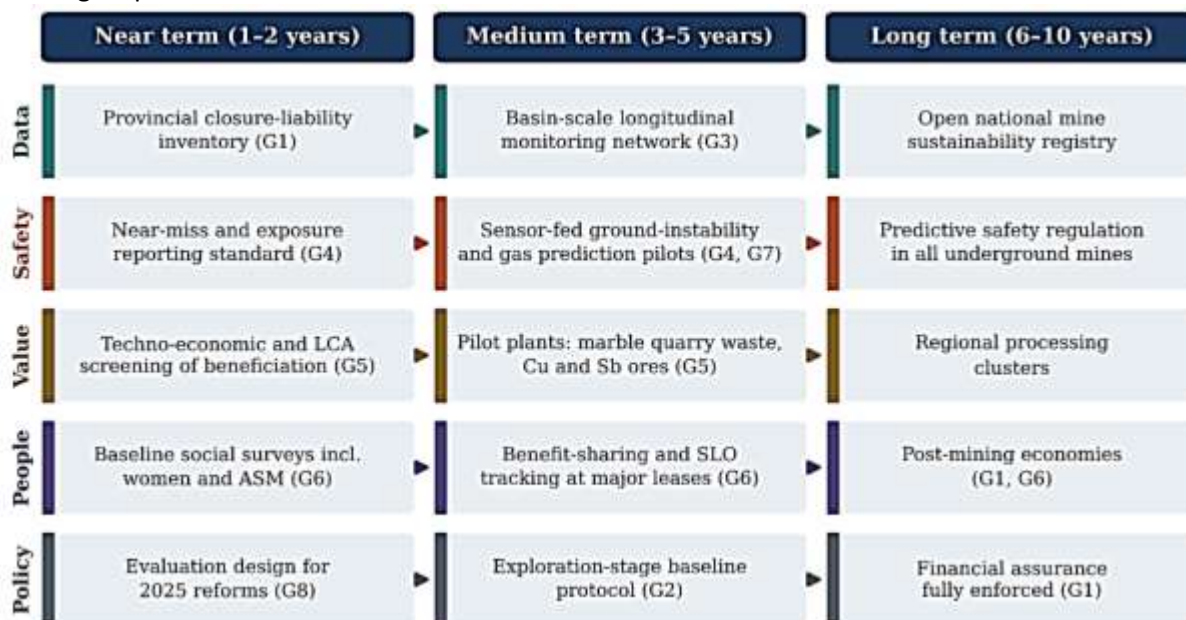


Figure 5. Roadmap linking the eight evidence gaps (G1–G8) to research and policy actions over a ten-year horizon. Source: authors conceived.

4. Conclusion

This review of 77 sources shows that the knowledge needed to manage that turning point sustainably is uneven. Site-level studies document contamination forest loss and occupational fatalities at working mines, but the stages before and after extraction are absent from the reviewed national literature the case for value addition rests on laboratory results and current technological and policy changes have not been evaluated. In response the paper offers an evidence-gap map an implementation-gap chain of four losses between statute and outcome the LISG framework with twelve lease-level indicators and eight research directions sequenced over ten years. All four await testing against a systematic search and field data. Regulators should first build a public registry of leases with baseline safety environmental and closure indicators. Operators should recognize that demonstrable performance is becoming a condition of finance and market access. Researchers should turn to the neglected ends of the life cycle and to why rules fail.

Declarations

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Use of artificial intelligence. A generative AI assistant was used to enhance the quality of English language.

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