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TOWARDS A FUTURE-ORIENTED CONCEPTUAL FRAMEWORK FOR MINE CLOSURE IN SAUDI DESERT ENVIRONMENTS: AN INTEGRATED PERFORMANCE-BASED APPROACH

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Abstract: *Mine closure in arid and semi-arid environments faces persistent challenges due to extreme climatic conditions (fragile ecosystems, uneven hydrology, and high wind speeds) and long-term stability requirements. Particularly in mineral-rich countries like Saudi Arabia, closure approaches are more complex due to the disciplinary silos; regulatory frameworks are general and not easily adaptable. Therefore, this research communication proposes the Saudi Arid Mine Closure Standard (SAMCS), a conceptual, future-oriented, integrated, and performance-driven framework to address the existing gaps. The core objective of this framework is to support effective mine closure planning that has been proposed precisely through a comprehensive consideration and integration of governed Saudi mine closure policies and legislations. This approach standardises the closure criteria and makes the approach applicable to a wide range of mine sites with similar closure challenges. This approach integrates the standard closure principles, desert ecosystem typology, performance-based closure acceptance criteria, and a minimum closure evidence package to provide a systematic pathway to evaluate good mine closure. Moreover, this framework supports sustainable mine closure aligned with Saudi Vision 2030 reforms. This study further outlines the Saudi mine closure regulatory architecture; the role of the Competent Authority in reviewing environmental compliance, monitoring results, and closure certification.*
Keywords: *mine closure, arid environments, performance-based closure, desert ecosystem, regulatory frameworks, competent authority*

1. Introduction

Mining is widely regarded as an important sector in national economic growth and revenue generation in many resource-dependent countries. It contributes to gross domestic product (GDP), export income, and government revenue that support public investment in infrastructure development, education, and employment generation [1]. Majorly, in arid and semi-arid countries like Saudi Arabia, the importance of mineral resources is especially high because alternative land-based economic activities are constrained by limited water availability, fragile ecosystems, and extreme climatic conditions [2]. According to an official announcement of Saudi Press Agency in April 2024, the Saudi Arabian government revised the Kingdom's mineral wealth estimate, increasing it from approximately SAR 5 trillion (~$1.33T) (2016 estimate) to SAR 9.4 trillion (~$2.5T) following extensive geological surveys and expanded exploration data[3]. Besides, these arid regions face a structural governance gap: no nationally specific, auditable standard exists to define what constitutes acceptable mine closure in hyper-arid desert conditions.

Mine closure is a regulatory process that transforms mining landscapes into environmentally stable, socially acceptable post-mining environments. Historically, many industries have not planned for premature closures due to cheaper commodities, low-grade resources, high production costs, and other technical and political constraints.

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Moreover, less priority was given to mine closure, which was considered the last stage of the mine cycle. In arid regions, poor management of mine closure activities severely disrupts ecosystem resilience and becomes a long-term burden on the government and society. Therefore, mine closure is considered a global challenge and a critical phase in the mining life cycle. Inadequate planning and post-closure land management can lead to prolonged monitoring requirements, costly remediation measures, and loss of public trust in the mining sector. Over the last two decades, mine closure has evolved from a technical end-of-life consideration into a central pillar of responsible mining governance and sustainable resource development [4].

Despite awareness of mine closure risks, existing closure policies and regulatory frameworks often remain general and inconsistently applied. As evidence, many case studies revealed that major mining-dependent countries such as Australia, Brazil, Canada, and South Africa may close mines prematurely, and fewer mine sites have been successfully relinquished [5]. In many current approaches, general rehabilitation goals are not sufficiently adapted to arid environmental conditions. Moreover, mine closure planning is generally differentiated and bounded to disciplines such as environmental, engineering, geological, hydrological, and governance considerations, which are often isolated. These general frameworks are unable to evaluate cumulative risks and long-term system behaviour, particularly in desert environments where landform stability, drainage, dust, and ecological processes are tightly coupled [6]. Therefore, a conceptual, policy-aligned, and integrated mine-closure framework is extremely needed for the Saudi mining industry's fast expansion and the environmental sensitivity of arid environments.

In this regard, the present study aims to propose a standard, future-oriented mine closure plan for arid environments that considers existing limitations. It represents a conceptual development of the Saudi Arid Mine Closure Standards (SAMCS) for evaluating closure outcomes across environmental, engineering, geological, hydrological, and governance aspects of mining sites. This study intentionally excludes site-specific case studies, detailed engineering designs, closure cost analyses, or social considerations; rather, it provides clarity on the mine closure acceptance criteria and systematically evaluates closure performance using transparent, auditable, and interdisciplinary criteria.

2. Conceptual and Regulatory Foundations for Mine Closure Good Practice

Mine Closure Frameworks and regulatory bodies in the context of Saudi Vision 2030

The systematic ending process of mining operations, a critical component for sustainable mineral development, and restoring the disturbed land to a stable, safe, and non-polluting state, is known as mine closure. To ensure long-term risk reduction, rehabilitation focuses on restoring ecological functions, drainage systems, and landforms. International closures for mines are measured against four primary closure objectives (relinquishment, long-term landform stability, public safety, and environmental protection) [7]. Over the last twenty years, many international organizations and regulatory bodies have published guidelines and frameworks that demonstrate the importance of planning, conducting, and assessing mine closure throughout the entire life cycle of a mine rather than treating it as an end-of-life responsibility [8]. The conceptual mine closure framework starts with progressive planning and extends to post-closure management, as illustrated in Fig. 1.

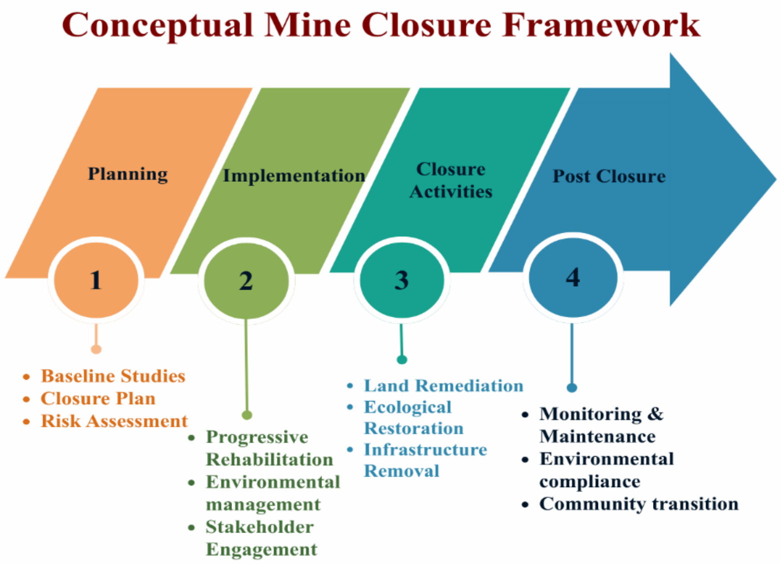

Fig. 1. Conceptual Mine Closure Framework Illustrating Progressive Planning to Post-Closure Management

Saudi Mine Closure Legal Architecture

Saudi Vision 2030 considers environmental sustainability, land rehabilitation, and resource development as core elements in national economic diversification. In this policy context, mine closure is recognised not only as an environmental commitment but also as a strategic governance instrument for protecting and water resources, and long-term socio-environmental value in arid regions [9]. International mine closure frame works such as the International Council on Mining and Metals (ICMM), the World Bank, and the International Finance Corporation (IFC), International Organization for Standardization (ISO), and leading mining jurisdictions such as Governments of Australia, Canada, and the European Union (EU), provide conceptual foundation that includes early integration of closure planning, identification and management of long-term environmental and physical risks, stakeholder engagement, financial provision for closure liabilities, and the establishment of clear criteria for closure completion and relinquishment [10], [11]. Saudi Vision 2030 reforms have established robust environmental regulations through comprehensive laws, mandatory environmental impact assessments, and specialised national centres covering vegetation, wildlife protection, desertification control, and meteorology. The Saudi Environmental Law (Royal Decree No. M/165 of 2020) provides the legal foundation for environmental protection, pollution control, and sustainable land management [12]. Under the Mining Investment Law (Royal Decree) of Saudi Arabia, mine rehabilitation and closure plans are explicitly mandated in licence documentation and environmental permitting requirements.

(i) Closure obligations

According to the Mining Investment Law, Article 34-35**,** an applicant for mining license approval (including exploration, small mine/ general purpose) is required to submit environmental and social impact assessments along with plans that align with environmental protection obligations and social considerations. Article 37(1) obligates an exploitation license holder must provide a financial guarantee for reclamation and closure in agreement with the nature of mining activity [13].

(ii) Environmental permitting/ EIA logic

In accordance with the Mining Investment Law (Royal Decree) of Saudi Arabia, Article 35(1), a mining license application must include an environmental impact assessment (EIA) and a detailed site reclamation and closure plan that demonstrates required actions for preservation and protection of natural resources and biodiversity [13].

(iii) Closure financial guarantee and release conditions

According to the Mining Investment Law (Article 37(1)-(2)), the license holder must provide the financial guarantee for reclamation and closure to grant an exploitation licence. The funds and conditions of the guarantee are determined by the executive regulations. After the verification of the environmental authority, only the guarantee may release the approved reclamation plan [13]. This article is the core Saudi regulatory framework that frames financial assurance and release conditions connected to closure implementation.

(iv) Closure certification/ relinquishment pathway

The provisions applicable to issuing a certification of mine closure and relinquishment are mentioned in Mining Rules Article 96. The Ministry shall issue the Certificate of Rehabilitation and Closure upon completion of the final performance evaluation, all requirements and obligations [14].

Role of the Competent Environmental Authority in Mine Closure

A competent authority is a Ministry/ any designated national centre within the environmental sector, operating within its legal jurisdiction as determined by the applicable regulations [15]. The National Center for Environmental Compliance (NCEC) is legally designated the Competent Authority for Saudi Arabia’s Environmental Law and mining regulatory framework. It was established by the Council of Ministers on March 26, 2019. NCEC is responsible for environmental permits, Environmental Impact Assessment (EIA) conditions, and compliance monitoring for mining projects. This government authority has developed several digital laws (environmental licenses, permits, and inspections) and a consolidated database for all environmentally detrimental activities. Approval from the competent authority is mandatory for environmental permitting for mining activities. The license holder must demonstrate all the environmental permit conditions, rehabilitation measures, and post-closure performance criteria to the competent authority before mine closure certification. Environmental compliance confirmation by this authority is a prerequisite for closure certification. In coordination with the competent authority, formal closure certification and relinquishment decisions are issued by the Ministry of Industry and Mineral Resources [16].

Principles of Good Mine Closure Practice

A set of widely accepted principles, including early planning, stakeholder engagement, adaptive management, and performance-based evaluation, that guide good mine closure practice [17]. The closure method can be tailored to meet local environmental conditions; it may offer advantages in arid or semi-arid

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environments where geomorphic / hydrologic systems are very responsive. However, interdisciplinary coordination for closure planning remains one of the most significant challenges. Environmental, geotechnical / mining engineering, geological, hydrological, and administrative/governance aspects are generally treated separately by different professionals, thereby limiting the ability to identify total risk and predict long-term behaviour of the entire system [18]. The interdependency of stability in landforms, surface drainage, dust generation, groundwater flow, and ecological recovery makes an integrated closure planning crucial.

3. Saudi Arid Mine Closure Standard (SAMCS): Conceptual Basis for Desert Environments

Conceptual Architecture of SAMCS and Standard Principles

The Saudi Arid Mine Closure Standard (SAMCS) is a performance-based, standardised approach to addressing recurring mine-closure problems, particularly designed for good mine closure practice in desert environments. SAMCS establishes logical evidence that describes what constitutes acceptable closure performance, how it should be evaluated, and what minimum evidence is required to support regulatory acceptance and post-closure accountability.

The proposed SAMCS is structured as an integrated package comprising four mandatory components, as shown in Fig. 2. These components ensure that mine closure is performance-based, context-specific, integrated, and auditable.

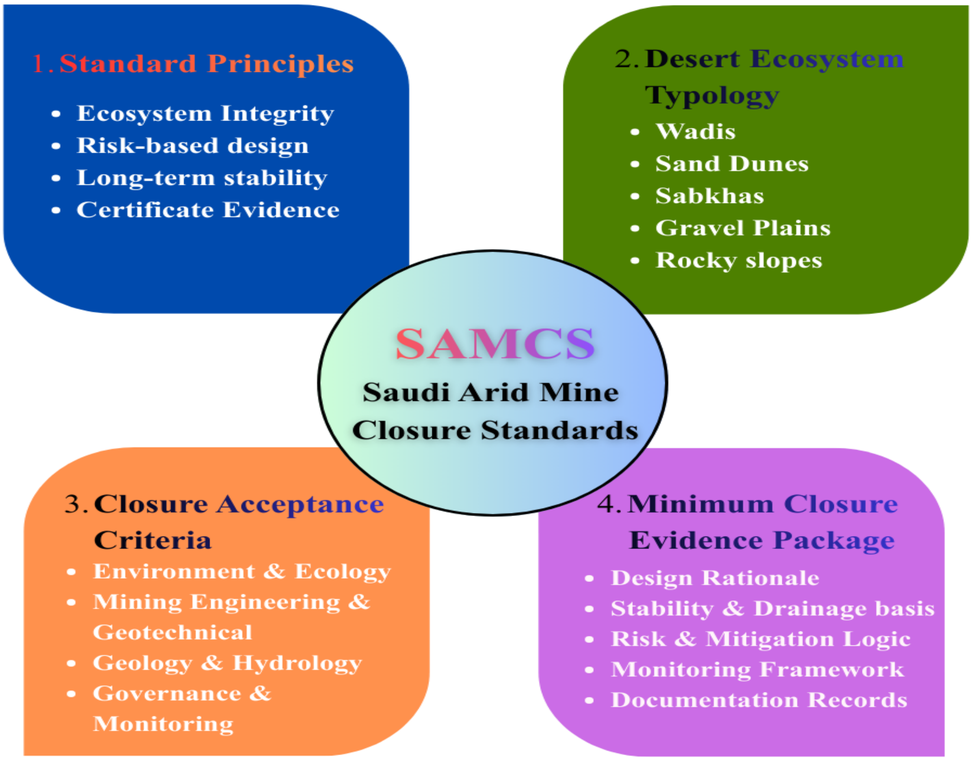

Fig. 2. Conceptual representation of the Saudi Arid Mine Closure Standards (SAMCS)

Standard principles are the governing principles that can satisfy fundamental expectations of all mine closure outcomes and should not prescribe any engineering solutions. Examples include: protection of desert ecosystem integrity, risk-based closure design, long-term physical and environmental stability, and provision of verifiable documentation to support regulatory approvals and relinquishments.

The desert ecosystem typology classifies the Saudi arid environment in a simple way to describe the ecological and geomorphological settings of closure. The primary goal of this classification system is to identify ecosystem-specific restrictions that closure designs cannot violate, ensuring that rehabilitation and landform design are consistent with natural desert processes and limitations. Saudi Arabia has a variety of desert landforms that are important to consider for closure design. Major Wadis traverse the Najd and central regions, providing periodic drainage flow paths. Extensive dunes and salt crust-covered sabkhas are located on the Arabian Gulf and Red Sea coastal plains in Saudi Arabia. Gravel plains dominate plateaus such as Al-Hamad and As-Summan, and rocky escarpments, including the Tuwaiq and Sarawat ranges, characterize rugged slope environments [19], [20]. The classification of Desert ecosystem typology is briefly listed in Table 1.

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Table 1. The classification of Desert Ecosystem Typology, Key constraints, Closure design implications

Desert Ecosystem Type	Key Constraints	Closure Design Implications	References
Wadis	Flash flooding, Soil erosion	Flood compatible and non-blocking natural drainage conveyance using grade-control structures, energy dissipation measures, and channel stabilization, erosion-resistant landforms	[21]
Dunes	Wind erosion, mobility	Surface chemical stabilisation (Binding materials: silt, clay, organic matter, and cement), Native dune vegetation (Haloxylon Persicum, Acacia ehrenbergiana, other psammophytes, etc.)	[22], [23]
Sabkhas (Flat salt-crusted deposits)	Salinity, low bearing capacity	Avoid load concentration, saline-tolerant restoration	[24]
Gravel plains	Surface armouring, Low vegetation cover, Limited Soil	Minimal disturbance, dust control	[25]
Rocky slopes/ outcrops	Limited soil, Physical stability issues	Preserve natural stability, avoid regrading	[26]

Closure acceptance criteria are the core operational element of SAMCS. "Acceptable closure" is defined through performance-based criteria across four integrated domains: (i) environment and ecology, (ii) mining engineering and geotechnical stability, (iii) geology and hydrology, and (iv) governance and monitoring. These criteria enable the consistent evaluation of closure performance in arid conditions. A minimum closure evidence package is required to monitor the outputs needed to demonstrate compliance with SAMCS. During closure approval and relinquishment, SAMCS improves the auditability, supports transparent regulatory decision-making, and reduces uncertainty.

Performance-Based Closure Acceptance Criteria

The key objective of a performance-based closure criterion is to regulate and apply broadly across different mine sites and scales. It should be well-structured using a framework approach, enabling flexibility and adaptability for local, site-specific conditions. Therefore, this closure approach is easily adaptable and aligns with the legislation of provincial and territorial governments [27], [28]. For instance, a performance-based approach focuses on outcomes rather than describing the exact numerical values of slope angles or surface treatments. This approach may state that final landscapes must be stable under defined rainfall and wind speeds without reliance on perpetual maintenance. In the same way, ecological closure success is not judged by the number of plants or the types of species (vegetation) used, but rather by whether native vegetation can survive and persist under desert conditions over time. In this regard, SAMCS is designed as an integrated, multifaceted process that requires extensive planning, supervision, and execution to ensure the long-term environmental and social stability of the site [28].

Auditability and Evidence-Based Closure

A critical component of performance-based closure is auditability**.** This will transform closure objectives from ambitious statements into acceptable standards by providing evidence that allows independent verification by regulators, auditors, and stakeholders. Therefore, each performance criterion is linked to an exact set of documentation, monitoring data, and verification procedures through auditable closure requirements [28]. To demonstrate long-term geotechnical stability, it will be necessary to document several things. These include documented design assumptions, stability analysis, and post-closure monitoring records, which verify actual performance during actual climate events. Regulatory approval and, eventually, relinquishing responsibility to local jurisdictions (in arid regions) will be difficult without auditability, as closure-related risks may take decades to materialize. Performance-based and auditable closure frameworks enhance long-term accountability, reduce uncertainty, and provide clarity by establishing standardized minimum evidentiary requirements.

4. Functionalizing SAMCS: Performance Requirements and Evaluation Framework

Purpose, Closure Domains, and Standard Elements of SAMCS

This section examines the core aspects of SAMCS that influence closure success, based on its performance requirements, acceptance criteria, and expected evidence. SAMCS is not a descriptive closure

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but a structured, standardized, outcome-based framework applicable in arid environments. This proposed standard is developed from four integrated domains that support environmental protection, engineering stability, subsurface integrity, and long-term governance.

Environmental/ecological performance requirements for long-term compatibility of post-mining landscapes in arid conditions are the primary focus of SAMCS. In this context, closure will demonstrate that restored areas are not polluting, are resilient to wind and water erosion, and can sustain native vegetation without constant maintenance. Success is indicated by the long-term persistence and self-sustainability of native species, effective dust suppression, and no secondary environmental degradation (i.e., the establishment of invasive species/the development of saline soils) [29]. Mining engineering/geotechnical requirements address the physical safety and stability of post-closure landforms. Under SAMCS, waste dumps, pit slopes, and reshaped terrain must be physically stable and resistant to failure in arid conditions, including intermittent, heavy rainfall and prolonged wind exposure.

Geo-hydrological requirements of SAMCS assure that closure designs are compatible with the character of groundwater regimes in arid regions. Accordingly, post-closure landforms must allow for continued drainage pathways and episodic wadi flow, with no sedimental blocking of these pathways; also, stable, on-contaminating interactions with pits, backfilled areas/terminal water bodies [30]. The success of closure is assessed in terms of hydrological function and geochemical stability, rather than the installation of specific drainage structures. According to SAMCS, transparency in evidence and auditability of evidence trails, documentation of responsibilities, and monitoring activities provide the basis for long-term accountability and regulatory trust required for a successful mine closure in arid environments. While governance frameworks should satisfy the acceptance criteria, monitoring the closure outcomes remains stable beyond active management periods.

To ensure that the proposed mine closure framework is comprehensive and robust, discipline-specific questions were formulated across the Environmental/Ecological, Geological/Hydrological, and Mine engineering domains. The questions were evaluated through conceptual prompts and aligned with relevant references. Tables 2a, 2b, and 2c collectively summarise selected key questions, the corresponding conceptual prompts, and the supporting references.

Table 2a. Environmental / Ecological questions related to mine closure, conceptual prompts and reference sources applied in framework formulation

S. No	Environmental / Ecological Questions	Conceptual Prompts	Reference
1	What is the core environmental objectives of mine closure?	The core objectives in environmental perspectives are • Protection of water resources • Physical and chemical stability of the ecosystem and recovery • Prevention of long-term environmental liabilities	[31], [7]
2	Is environmental rehabilitation legally required after mine closure in Saudi Arabia?	Yes. According to Saudi environmental law, Environmental rehabilitation and restoration are mandatory.	[32]
3	How are water resources treated in conceptual mine closure frameworks?	The development of pit lakes may be one possible closure outcome under favourable hydrogeological and geochemical conditions, with explicit risk controls and maintaining sustainable post-closure water balances in arid and semi-arid regions.	[33], [34], [35]
4	How is waste, tailings, and acid mine drainage rehabilitation addressed conceptually?	To prevent contamination and erosion of land, waste rocks and tailings are treated as engineered landforms designed for long-term physical and chemical stability. Acid mine drainage (AMD) should be identified early and managed through selective handling and isolation to limit exposure to oxygen and water.	[36], [37]
5	How can environmental approvals align with long-term sustainability goals such as Vision 2030?	Environmental approvals can align with the sustainability goals of national development visions by integrating closure planning, environmental stewardship, and post-closure land-use.	[9], [38]

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6	Why should environmental and closure costs be considered during strategic mine planning rather than at the end of mine life?	Early consideration of mine closure during strategic mine planning ensures a realistic assessment of environmental liabilities, improves decision-making, and minimises long-term closure risks.	[39]
7	What constitutes "good practice" in mine closure at a conceptual level?	Good practice includes early planning, legal clarity, progressive rehabilitation, community engagement, post-closure monitoring, and financial assurance.	[40]
8	Can renewable energy development mitigate environmental pressures in arid industrial regions?	Yes. Arid and semi-arid regions such as Saudi Arabia offer high solar potential, enabling renewable energy use to reduce carbon emissions and support sustainable industrial development.	[41]

Table 2b. Geology / Hydrology questions related to mine closure, conceptual prompts and reference sources applied in framework formulation

S. No	Geology / Hydrology questions	Conceptual Prompts	Reference
1	How do surface disturbance and mine voids modify natural recharge pathways?	• Surface disturbances (stripping, compaction) decrease permeability. • Coarse spoils and fractures enhance vertical percolation. • Removal of vegetation increases net infiltration in arid and semi-arid conditions. • Mine voids (open pits, subsidence zones) act as hydraulic sinks.	[42], [43]
2	How do geomorphic processes evolve on reclaimed landforms over the years?	• In the early years, high erosion rates dominate due to limited vegetation and the formation of rills and gullies. • Between 5-20 years' time span, vegetation increases, surfaces become stable, sediment yields decline, and drainage networks become more organized. • After 20 years, slopes gradually decrease with diffusive processes, soil structure develops, and erosion rates return to ground levels.	[42], [44]
3	How do faults and fractured networks control groundwater flow in post-mining terrains?	Faults and fracture networks strongly control the groundwater flow direction, velocity, and connectivity. (Mining activities- Blasting, pit excavation, and dewatering)	[42], [45]
4	What hydrogeological risks persist even decades after mine closure?	Persistent hydrogeological risks after mine closure include uncontrolled discharge of mine water rebound, acid-rich drainage, mobilization of contaminants, and tailings.	[46]
5	How can mine design adopt a systems-thinking approach that integrates geology, hydrology, engineering, and ecology?	• Mine design should start with a Single Integrated Conceptual Site Model that links resources, pathways, and receptors. Then design an integrated water balance, contact/non-contact separation, flood routing, and seepage control considering geological structure and hydrogeology. • Translate geochemistry into design controls. • Required to use risk-based scenario-driven decisions (Ex, extreme rainfall/climate variability, failure modes, long-term performance)	[7], [47]
6	How does climate change influence contaminant leaching and hydrological balance?	Climate changes such as Extreme rainfall (intensifies the solubility of acids and salts); Higher temperatures (Accumulate salts and amplify metal/sulfate loads) change the dilution capacity of groundwater.	[48], [49]

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Table 2c. Mining Engineering questions related to mine closure, conceptual prompts and reference sources applied in framework formulation

S. No	Mining Engineering questions	Conceptual Prompts	Reference
1	How does mine design influence long-term environmental stability after mine closure?	Mine design controls erosion, geotechnical stability, and post-closure contamination by determining the final landform geometry, drainage systems, and groundwater balance. Integrated closure designs reduce the legacy risks.	[7], [50]
2	What are the dominant failure risks associated with tailings storage facilities at the closure stage?	Dominant failure risks include overtopping, slope instability linked to pore pressure, internal pipe erosion/corrosion, and surface erosion.	[51]
3	What design strategies can minimize future environmental liabilities associated with mine wastes?	Recommended strategies: • Life cycle planning, progressive rehabilitation, and reducing the residual risks • Conservative design • Long-term monitoring Recommended practices: • Prioritize source control (segregation/encapsulation) and robust water management (clean-water diversion, impacted-water collection/treatment). • Embed progressive rehabilitation into the operational schedule with measurable criteria.	[7], [52]
4	What pathways enable contaminant migration from mine sites to surface water bodies?	Contaminants can migrate through surface runoff/erosion, drainage channels, groundwater discharge/seepage, accidental releases, and abandoned mine drainage.	[53]
5	How does waste rock characterization affect acid mine drainage potential?	Mine drainage can form when sulfides oxidize, producing acidity and mobilizing metals, which affect surface and groundwater quality.	[54]
6	How should mine design anticipate the long-term geochemical behaviour of waste materials?	• Best-practice ARD guidance recommends characterization and prediction (static and kinetic tests) to estimate when drainage may form, and then translating the results into design controls. • Lifecycle materials management guidance emphasizes integrating geochemistry with mine planning and facility design to prevent/reduce long-term pollution and closure liabilities.	[7], [52]
7	How does designing for closure differ conceptually from designing for production?	• Production design prioritizes extraction efficiency and short-to-medium term economics; Whereas closure design prioritizes long-term stability, low residual risk, and achievable end-states after active management declines.	[7]

Integrated Closure Evaluation Framework: From Liability to Living Landscape

The mine closure requirements are particularly tied to a performance-based acceptance criteria approach and lack sufficient documentation to convert the SAMCS into a functional and auditable evaluation tool. The approach of SAMCS is based upon a forward-thinking view of closure, that a well-planned closure of mines in arid regions can lead to the creation of fully-integrated, ecologically cohesive systems that will generate both environmental and social benefits for an extended period beyond closure itself, and not just serve as a final point in terms of regulatory compliance. This strategic approach will ensure closure outcome assessment based on proven long-term performance rather than providing interim remediation. To provide uniform regulatory review of all arid mining conditions, the framework integrates environmental, geological, hydrological, and governance-related factors.

Where the hydrogeological characteristics of a site permit it, water can be recovered into terminal pit lakes and developed as ecological assets; terracing of pit margins creates varied microhabitats, and native vegetation can be established along pond margins early in the rehabilitation process. Excavated material reshaped into rehabilitated landforms can be designed to integrate with the surrounding desert, planted with locally sourced desert flora, and structured to provide passive recreational value, walking routes, observation points, or low-impact overnight use, without creating maintenance obligations incompatible with arid conditions. The existing infrastructure at sites such as accommodations, workshops, and roadways should be evaluated as a first step prior to demolition to determine whether there are opportunities to repurpose the existing structures

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for alternative purposes. These programs would complement the goals stated in Vision 2030 to develop a nature-based tourism industry and establish an environmental identity in Saudi Arabia.

A critical element of the SAMCS approach is to identify and protect biological heritage assets (including long-standing trees and mature vegetation that existed before mining ("heritage trees" or "mother trees") throughout all phases of each project. Biological heritage assets should be identified and documented, protected in place wherever feasible, and when necessary, relocated and incorporated into design elements of the closure landform. Monitoring activities should begin at the commencement of each project and continue through operations and into the post-closure phase to ensure continuous ecological function and data quality throughout the life cycle of each mine operation. The SAMCS closure evaluation matrix is presented in Table 3.

Table 3. The SAMCS closure evaluation matrix maps standard requirements to performance-based acceptance criteria along with derivation notes and associated evidence across the four-closure domain

Closure Domain	**Standard Requirement**	**Performance-Based Acceptance Criteria**	**Criteria Derivation Notes (Baseline / Design Event / Monitoring)**	**Minimum Required Evidence**	**References**
Environment / Ecology	Long-term control of dust emissions from post-closure landforms	Measured dust particulate levels and erosion indicators remain within the regulatory environmental measurement limits and not to exceed baseline variability under extreme wind conditions.	Baseline window: More than 2 years data of operational dust monitoring Design event: Regional extreme wind conditions (For example: A 1:50-year wind event refers to an extreme wind condition with a 2% probability of occurrence in any given year) It is commonly used as a design benchmark for engineered landforms and infrastructure. Monitoring frequency: Quarterly post-closure dust monitoring to observe seasonal variability of dust emissions and verify the stability of dust control measures. Quality Assurance (QA) /Quality Control (QC): calibrated particulate matter monitors, multiple sampling, certified laboratory analysis.	• Regular dust monitoring datasets • Erosion monitoring records • Instrument calibration logs • Monitoring QA/QC documentation • Compliance assessment reports.	[7], [15]
Environment / Ecology	Establishing self-sustaining native vegetation and the prevention of invasive species (non-local)	Plantation of native vegetation, which can survive and continue its life cycle using natural rainfall and local soil moisture. • No rapid growth of non-native species	Baseline: Two approaches are commonly used. 1. Pre-disturbance vegetation surveys (Documentation on natural vegetation species, plant density, soil condition, ecosystem structure etc. before start the mining) 2. Reference ecosystem analogues. (If the original site data is unavailable, a nearby undisturbed ecosystem used as bench mark) Monitoring: Annual vegetation surveys for more than 5 years QA/QC: standardized ecological sampling protocols and georeferenced monitoring plots.	• Selection of native species (site-specific) and restoration rationale. • Regular vegetation establishment and survival monitoring data. • Invasive species prevention and management plan	[7], [55]

Environment / Ecology	Post-closure landforms align with the desert ecosystem typology	Rehabilitated landforms align with the defined desert ecosystem typology (Wadis, Dunes, Sabkhas, and gravel plains)	Baseline: Regional geomorphic mapping and ecosystem classification. (Geomorphic mapping is a systematic method of identifying, classifying, and mapping landforms and surface features based on their formation process, such as erosion, sediment transport, deposition, weathering, and tectonic activity) Monitoring: periodic field inspections and geomorphic stability assessments (every 1–2 years).	• Surface stability verification using field inspections. • Geomorphic mapping records; • Rehabilitation design documentation.	[7], [56]
Mining engineering / Geotechnical	Long-term physical and structural stability of closure landforms	Final pit walls, waste dumps, and mine tailings demonstrate stability under extreme rainfall and seismic conditions.	Design events: Extreme rainfall returns periods (For example: 1:100-year storm means a storm magnitude that statistically has 1% probability of occurring in any given year.) and applicable regional seismic loading parameters such as peak ground acceleration (PGA), Earthquake return periods, Seismic stability analysis. Monitoring: (Quarterly / Annually / after extreme events) Monitoring of engineering design includes • Geotechnical inspections for cracks, slope movement, seepage, erosion, settlement etc. and remote sensing where applicable. • Instrumentation monitoring (Piezometer, inclinometers, survey monitoring points, remote sensing technologies if applicable)	• Slope stability and landform design analyses • Flood and erosion modelling outputs	[7], [57],[58]
Mining engineering / Geotechnical	Identification and mitigation of failure mechanisms	• At closure, all credible failure mechanisms have been identified and appropriately mitigated, ensuring that no unmanaged risks remain. • Closure designs do not depend on frequent maintenance	Risk assessment: systematic failure mode identification during closure planning. (For example: Slope instability in waste dumps/pit walls, tailings storage failure, drainage failure, structural degradation of cover systems etc.) Monitoring: periodic stability verification and risk review.	• Built closure design documentation • Residual geotechnical risk register • Technical review reports	[7], [50]

Geology / Hydrology	Groundwater systems protection from closure-induced impacts	Stabilize groundwater flow and quality and maintain consistency with baseline conditions.	Baseline window: More than 2 years of groundwater monitoring before closure. (Parameters: ground water level, pH, dissolved metals, salinity, sulfate concentrations etc.) Monitoring frequency: Semi-annual (in both wet and dry seasons) groundwater level and quality monitoring post-closure. QA/QC: standardized sampling procedures with proper sample preservation and certified laboratory analysis.	• Conceptual site water balance model • Groundwater and surface water monitoring data • Drainage design logic and flood routing analysis Water quality baseline and predictive modelling	[59]
Geology / Hydrology	Compatibility of closure landforms with natural drainage and wadi systems	Safe post-closure drainage systems (wadis and storm flows) without any sedimental blockage and downstream impacts.	Design events: Regional storm return periods (For example, 1:100-year rainfall). Monitoring: Inspections and periodic drainage system assessment after storm effect. QA/QC: validated hydrological modelling and field verification.	• Surface-water and flood modelling • Drainage design rationale • Post-event inspection records • Sediment transport	[7], [59]
Governance / Monitoring	Demonstrable compliance with closure acceptance criteria	Closure performance is supported by verifiable, traceable, and complete evidence suitable for independent technical and regulatory audit.	Monitoring: defined program covering various indicators such as Ecological (Vegetation cover and species diversity, ecosystem stability, soil development, habitat functionality, fertility etc.); Hydrological (Ground water levels and quality, drainage system performance, seepage etc.); Geotechnical (Physical stability of engineered landforms, erosion rates etc.). QA/QC: documented monitoring protocols and data validation procedures.	• Closure performance reports; • Monitoring datasets with documented quality assurance / control • Individual audits / review reports • Evidence traceability matrix.	[7], [60]
Governance / Monitoring	Readiness for regulatory acceptance and relinquishment	All closure acceptance criteria are met, monitoring demonstrates long-term stability, and residual risks are formally assessed and accepted by the regulator.	Monitoring period: sufficient duration to demonstrate system stability (It depends on the site). Verification: Monitoring outcomes and closure documentation are reviewed by regulator.	• Residual risk assessment; • long-run monitoring outcomes; • formal regulatory acceptance records.	[7], [59]

5. Alignment of SAMCS with Saudi Vision 2030 Mining Reforms

Saudi Vision 2030 aims to position mining as the third pillar of the Saudi economy by increasing mining's contribution to GDP SAR 97 billion to GDP by 2020 and creating approximately 90,000 direct and indirect jobs in the mining sector. According to 2024 Annual report of Saudi Vision 2030, Public Investment fund (PIF) has grown from SAR 720 billion in 2016 to SAR 3.53 trillion in 2024 (portion of these funds directed towards mining projects). Due to significant investments in the mining sector, non-oil revenues have increased by 171% since 2016 [61].

Responsible mine closure is a critical enabler for this goal, and not a mere expense. SAMCS contributes to the realization of the goals of Saudi Vision 2030 in five direct areas:

• **Responsible mining and environmental protection:** SAMCS provides a quantifiable and independently verified measure of how Saudi Arabian mining operations will meet their closure obligations as part of their international investor relations, government interactions, and environmental, social, and governance (ESG) ratings from rating agencies.

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• **Improved governance and compliance:** SAMCS enables clarity, consistency, and certainty for all parties involved by clearly defining the closure criteria for all mining operations in Saudi Arabia. This enables all parties to avoid the high administrative and financial risks associated with disputed closure negotiations between the Ministry of Industry and Mineral Resources (MIMR) and mining operators.
• **Reduction of long-term liability:** SAMCS requires mining operators to close mines based on performance, monitors these closures, and retains financial assurances. These measures reduce the risk of abandonment or orphaning, which would ultimately lead to costs to the state.
• **Measurable sustainability and ESG outcomes:** SAMCS provides the audit trails required by mining operators to report their ESG results. As such, SAMCS enables mining operators to provide quantitative closure performance metrics to their investors and other stakeholders.
• **Nature-based tourism and desert identity:** The integrationist approach to mine closure outlined in SAMCS, using native plants to restore habitats and adapting existing mine structures into new uses, is directly consistent with Vision 2030's intention to promote nature and eco-tourism as national economic sectors [9], [38]. Fig.3 illustrates the concept of integrated, nature-based mine-closure.

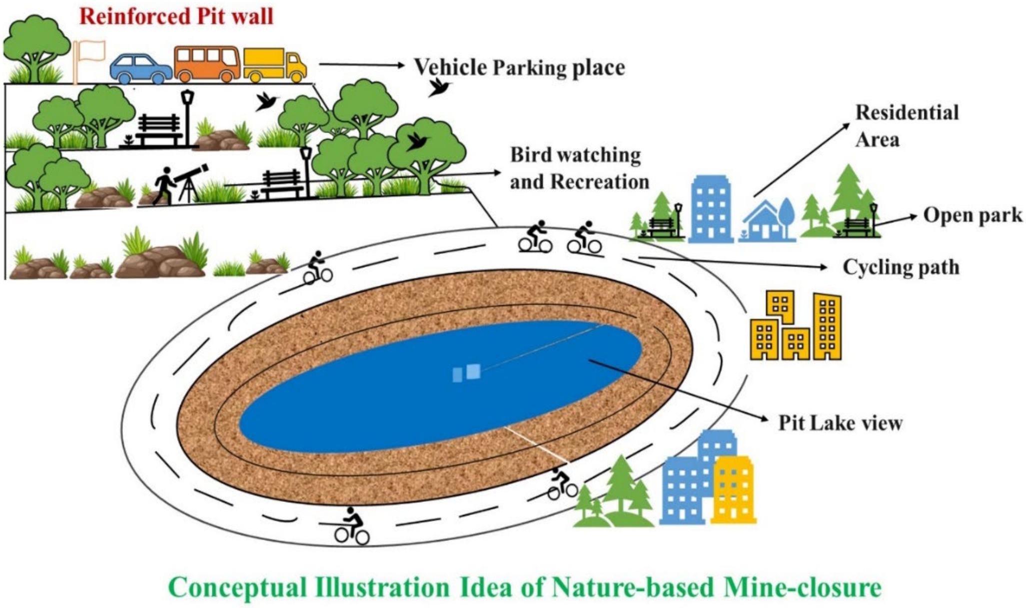

Fig. 3. Conceptual Illustration of integrated, nature-based mine-closure.

6. Conclusions

Saudi Arabia's expanding mining sector requires a nationally applicable, technically robust mine closure standard to be developed with respect to both ecological and geological conditions in the hyper-arid desert environment. SAMCS represents an initial conceptual framework for this standard based on the integration of four interrelated aspects: foundational principles, desert ecosystem typology, closure acceptance criteria, and minimum closure package across four technical domains.

SAMCS has been designed to be achievable, neither overreaching in its ecological prescriptions nor technologically simplistic, to provide measurable, auditable closure outcomes that will decrease long-term environmental liabilities, increase ESG performance, and, ultimately, support the achievement of Saudi Vision 2030's objectives for sustainable development through responsible industrialization and environmental management. To avoid fragmentation, a single evaluative framework is developed by integrating environmental, engineering, geological, hydrological, and governance considerations. The proposed framework is specifically relevant to Saudi Arabia's arid landscapes, enables post-closure land use aligned with broader development goals, and directly contributes to the Saudi Vision 2030 reforms. The proposed framework is not site-specific, so it is readily adaptable to other arid and semi-arid mining regions with similar closure challenges. As empirical post-closure data become available, future work may focus on fine-tuning acceptance thresholds and piloting the standard at the site level.

Conflicts of interest
The authors declare no conflict of interest.

Ethical statement
The authors state that the research was conducted in accordance with ethical standards.

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