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Toward a Multidimensional Conceptual Framework for Sustainable Mining Districts: Advancing Strategic Territorial Planning in Colombia

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Abstract

Sustainable Mining Districts (SMDs) have recently emerged as a territorial governance approach for promoting sustainable mining; however, no integrated conceptual framework currently exists to support their strategic planning. This study develops the first multidimensional conceptual framework for SMDs by integrating evidence from the scientific literature, institutional analysis, and territorial characterization, using Colombia as an illustrative case. The results reveal a growing international research emphasis on sustainability, governance, and territorial planning in mining, together with an emerging institutional transition toward district-scale governance. These findings support the identification of eleven complementary planning dimensions—geological, mining, transformation, environmental, social, market, economic, financial, infrastructure, legal, and governance—that collectively characterize SMDs as integrated territorial systems rather than solely geological or administrative units. The proposed framework provides a structured conceptual basis for organizing multidisciplinary information and supporting strategic territorial planning through an illustrative set of key performance indicators (KPIs). Although conceived as a proof of concept requiring future empirical validation, the framework offers a foundation for evidence-informed planning and governance of mining territories in Colombia and other mineral-producing regions.

Keywords: sustainable mining districts; territorial planning; strategic planning; governance; mineral resources; critical minerals

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1. Introduction

1.1. Background

Mining districts (MDs) are geographically defined areas characterized by the concentration of mineral resources, mining activities, and associated economic linkages. Traditionally, they have been understood as production systems whose spatial configuration reflects geological endowment, mineral extraction, and historical mining development [1,2].

Although mining contributes to economic growth, employment, and infrastructure development, it also generates significant environmental and social pressures, including ecosystem degradation, water conflicts, greenhouse gas emissions, land-use competition, and social inequalities. These challenges have intensified the need to incorporate sustainability principles into strategic mine planning, particularly in regions where mining constitutes a major driver of territorial development [3–5].

Figure 1 illustrates the proposed multidimensional conceptual framework for Sustainable Mining Districts (SMDs). The framework conceptualizes SMDs as territorial systems integrating eleven complementary planning dimensions: geological, mining, transformation, environmental, social, market, economic, financial, infrastructure, legal, and governance. This perspective shifts the focus from individual mining operations to coordinated territorial planning that supports long-term regional development and contributes to the Sustainable Development Goals (SDGs).



Figure 1. Multidimensional conceptual framework of SMDs. Developed by the authors based on the proposed conceptual framework.

1.2. Research Gap

During the last two decades, sustainability has become a central theme in mining research. International initiatives such as the Sustainable Development Goals (SDGs), the International Council on Mining and Metals (ICMM) Mining Principles, the Global Reporting Initiative (GRI), the Initiative for Responsible Mining Assurance (IRMA), and Environmental, Social and Governance (ESG) frameworks have substantially improved sustainability assessment at the project and corporate levels. Likewise, studies on mining governance, regional development, industrial clusters, and resource-based territories have expanded the understanding of mining as a driver of territorial transformation.

In parallel, the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) has strengthened international best practices for the transparent, material, and competent public reporting of exploration results, mineral resources, and mineral reserves, providing a globally recognized foundation for technical disclosure and decision-making in the mining industry [6].

District-scale planning poses challenges that cannot be adequately addressed through project-level sustainability frameworks alone. MDs involve multiple deposits, heterogeneous actors, overlapping jurisdictions, interconnected infrastructure, cumulative environmental impacts, and complex governance structures that require coordinated territorial planning rather than isolated project management.

Colombia provides a particularly relevant context because the country has recently initiated the formal establishment of Special Mining Districts for Productive Diversification (SMDPDs) as territorial planning instruments through national public policy. Although this institutional process represents an important step toward integrating mining and territorial development, the conceptual and analytical basis for planning these districts remains at an early stage [7]. This creates an opportunity to propose a more comprehensive conceptual framework to support future implementation and evaluation.

To address this gap, this study proposes a multidimensional conceptual framework for SMDs that integrates eleven complementary planning dimensions derived from bibliometric evidence, institutional analysis, process tracing, and geospatial assessment. Although internationally recognized sustainability frameworks have substantially advanced responsible mining practices, they primarily assess individual mining projects, companies, or operational performance. None provides an integrated territorial planning framework that simultaneously incorporates geological, mining, transformation, environmental, social, economic, financial, legal, infrastructure, market, and governance dimensions at the MD scale. Rather than introducing a new analytical method, the proposed framework fills this conceptual gap by providing a structured basis for territorial planning and laying the foundation for future empirical validation, the operationalization of key performance indicators (KPIs), and application to emerging SMDs.

1.3. Objectives

The main objective of this study is to develop a multidimensional conceptual framework for the strategic planning and governance of SMDs, integrating geological, mining, transformation, social, environmental, market, economic, financial, infrastructure, legal, and governance dimensions to guide the transition from traditional MDs toward SMDs that promote economic diversification and shared value creation.

To achieve this objective, the study pursues the following specific research objectives (RO):

1. RO1. To examine the scientific evolution, knowledge structure, and emerging research trends related to MDs, sustainable mining, territorial governance, and planning frameworks through a bibliometric analysis.
2. RO2. To assess the institutional, legal, and policy instruments that influence the planning, creation, and governance of SMDs in Colombia.
3. RO3. To characterize the spatial distribution of mineral resources, MDs, and territorial planning instruments through geospatial analysis to identify key territorial attributes for SMD planning.
4. RO4. To develop a multidimensional conceptual framework for SMD planning that integrates eleven interrelated dimensions and proposes a set of KPIs to support strategic planning, monitoring, and governance processes.

1.4. Research Questions

To address the identified research gap and achieve the proposed objectives, this study is guided by the following research questions (RQ):

1. RQ1. What are the main scientific trends, knowledge structures, and emerging themes related to MDs, sustainable mining, territorial governance, and planning frameworks?
2. RQ2. Which institutional, legal, and policy instruments influence the planning and governance of SMDs in Colombia?
3. RQ3. What territorial characteristics and spatial relationships should be considered for the planning and management of SMDs?
4. RQ4. How can a multidimensional conceptual framework integrating planning dimensions and KPIs support the transition from traditional MDs toward SMDs?

2. Literature Review

2.1. Mining Districts

The scientific literature shows that MDs are increasingly analyzed as territorial systems that combine geological potential, mining production, environmental management, governance, infrastructure, and regional development processes, rather than solely as areas of mineral extraction. The countries with the largest volume of scientific contributions identified in this review are China, Ghana, and Colombia. At the same time, Canada, Peru, and Chile provide important benchmark experiences for MD planning and governance.

Internationally, MD research has evolved from predominantly geological investigations toward increasingly multidisciplinary perspectives. Canada, Chile, Peru, and China have mainly contributed to district-scale metallogeny, porphyry copper systems, gold camps, geophysical modeling, and exploration targeting, establishing important foundations for mineral resource assessment and regional geological evolution [8–16]. Peru has focused on copper geochemistry, environmental liabilities, soil contamination, resource depletion, and the socioeconomic implications of mining activities [17–21]. Chile has developed benchmark experiences in copper MDs through studies on mine planning, water–energy management, tailings, mineral processing, and socio-environmental conflicts [22–32]. China, which represents the largest body of literature identified in this review, has expanded the concept of MDs by integrating geological characterization with environmental monitoring, ecological restoration, remote sensing, machine learning, and environmental risk assessment [33–62]. In contrast, research in Ghana has concentrated on artisanal and small-scale gold mining, land-use change, water quality, community livelihoods, institutional arrangements, and mining governance, emphasizing the social and governance dimensions of MDs [63–83].

In Colombia, research on MDs has evolved from the geological and metallogenic characterization of gold, emerald, coal, and polymetallic districts toward studies addressing environmental impacts, mercury contamination, mine planning, territorial governance, and district-scale development strategies, reflecting a growing interest in multidimensional approaches to mining territories. Early contributions focused on the geological characterization of the Chivor Emerald District [84] and the technical and economic assessment of the La Llanada Gold District [85]. Subsequently, research expanded to major mining regions including the Segovia–Remedios Gold District [86–92]; the Bajo Cauca Gold District [93–95]; the Marmato Gold District [96]; the California–Vetas Gold District [97]; the La Llanada Gold District [98]; the San Juan Gold and Platinum District [99]; the Chivor–Muzo–Cosquez Emerald District [100,101]; the Amaga Coal District [102,103]; and the Cesar Coal District [104]. More recent studies have progressively incorporated environmental, social, economic, and governance perspectives, demonstrating a transition from predominantly geological investigations toward integrated territorial planning approaches for MDs [96,104–107].

2.2. Sustainable Mining

Sustainable development is a broad concept that includes social, economic, environmental, and governance elements. The most frequently cited definition is that of the Brundtland Commission in its 1987 report, *Our Common Future*, for the United Nations Secretary General [108], which defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [108,109]. In this context, sustainable mining aims to balance mineral resource development with environmental protection, social equity, economic development, and governance while strengthening the natural and human capital that supports long-term territorial sustainability [110].

At the territorial level, sustainable mining requires that mineral extraction generates lasting economic, environmental, and social value. Because mining projects differ substantially in their technical characteristics and territorial impacts, sustainability assessment should rely on flexible frameworks adapted to local conditions [108].

Since the Mining, Minerals and Sustainable Development (MMSD) initiative in the late 1990s, numerous sustainability frameworks have been developed for the mining sector. Many of these initiatives are aligned with the Sustainable Development Goals (SDGs), promoting responsible resource management, stakeholder engagement, and the maintenance of a Social License to Operate (SLO) through trust, transparency, and community participation [111,112].

In recent years, the principles of sustainable mining have reinforced the need to incorporate economic diversification into mine planning and operations. Diversification has traditionally been considered only in post-mining contexts; however, several authors argue that it should be integrated from the earliest stages of mining development to reduce territorial dependence on extractive activities and enhance long-term sustainability [113].

2.3. Governance

Sustainable mining extends beyond the operational performance of individual projects by integrating environmental stewardship, social inclusion, economic resilience, and responsible governance throughout the mining life cycle. Consequently, territorial governance has become a fundamental component of sustainable mining, enabling coordination among stakeholders, reconciliation of competing land uses, and alignment of mining activities with broader territorial development and sustainability objectives [110,111,114–117].

Globally, mining is becoming increasingly strategic for decarbonization and technological development because it supplies critical minerals required for renewable energy systems, electric vehicles, energy storage, and advanced technologies. Meeting this growing demand will require substantial investments and the establishment of stable institutional frameworks, long-term public policies, and transparent regulatory systems that balance economic, social, and environmental objectives [118]. In this context, governance provides the institutional foundation for coordinating these efforts across stakeholders.

Governance in sustainable mining involves the participation of multiple actors in decision-making and the implementation of policies, institutions, and processes [106]. Effective governance requires coherent legal and fiscal frameworks, strong regulatory institutions, transparent oversight, and mechanisms that reduce information asymmetries, strengthen accountability, and maximize the long-term public benefits generated by mineral resource development [118].

Recent research has highlighted the importance of territorial governance in MDs, emphasizing that planning and decision-making should evolve from isolated project-level approaches toward district-scale governance frameworks that coordinate public institutions, mining companies, local communities, and other stakeholders. Such approaches

align mining development with regional planning, environmental management, social participation, and economic diversification, providing an institutional basis for integrated territorial planning in SMDs [7,119–122].

2.4. Strategic Planning

The main purpose of mine planning is to design an integrated system in which mineral reserves are sustainably extracted and supplied to the market, maximizing the project's Net Present Value (NPV). Despite recent advances, sustainability principles are often incorporated only partially during the planning stage, limiting opportunities to mitigate environmental and social impacts from the earliest phases of mine development [114]. Consequently, strategic planning has become essential for integrating technical, economic, environmental, and territorial considerations into mining decision-making [123].

Among the available planning tools, Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is widely used to identify internal and external strategic factors that support decision-making and long-term planning [124]. When complemented with Correct, Adapt, Maintain, Exploit (CAME) analysis, SWOT provides a structured basis for selecting strategies that improve the sustainability and competitiveness of mining territories.

Beyond conventional planning tools, several complementary approaches have been proposed to strengthen sustainable mining strategies. Creating Shared Value (CSV) emphasizes the simultaneous generation of business value and socioeconomic benefits by aligning corporate objectives with community needs and the Sustainable Development Goals (SDGs), thereby contributing to risk reduction and stronger stakeholder relationships [112,125]. Likewise, cluster theory views MDs as territorial innovation systems in which interactions among firms, suppliers, research institutions, governments, and local communities enhance productivity, technological development, and economic diversification beyond mineral extraction [126–130].

Strategic planning must also address the challenges posed by climate change and the global energy transition. Achieving net-zero emissions requires long-term development strategies that integrate decarbonization objectives with territorial planning, recognizing that mining investments typically extend over decades and must remain aligned with evolving environmental, economic, and institutional conditions [131,132].

2.5. Existing Frameworks

The evolution of these frameworks reflects the growing incorporation of sustainability into mining practice. The ICMM Mining Principles (2003) established industry-wide principles for sustainable mining [133], followed by the Towards Sustainable Mining (TSM) initiative (2004), which strengthened corporate accountability and transparency in areas such as biodiversity, tailings management, community engagement, health and safety, and climate performance [134]. The Framework for Responsible Mining (FRM) (2005) proposed best-practice principles for responsible hard-rock mining [108], while the Leading Practices for Sustainable Development Program (LPSP) (2011) introduced practical guidance covering the entire mining project life cycle [108]. Subsequently, the Mining Policy Framework (MPF), developed by the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) (2013), promoted sustainability-oriented public policies [108], SUSustainable Operations (SUSOP®) (2010) incorporated sustainability criteria into early-stage mine design and mineral processing [135–137], the Extractive Industries Transparency Initiative (EITI) Standard (2013; updated in 2023) strengthened transparency and governance in extractive industries [138,139], and the IRMA (2018) established an independent certification framework for socially and environmentally responsible mining [108,140].

Among these initiatives, the GRI has become the most widely adopted sustainability reporting framework in the mining industry. Although the recently introduced GRI 14: Mining Sector 2024, effective from January 2026, substantially expands sector-specific reporting requirements, previous studies have identified limitations related to stakeholder participation, qualitative assessment, and the representation of local sustainability conditions [4,108,141].

Despite their valuable contributions, existing frameworks primarily assess sustainability from the perspective of individual mining companies, projects, operations, or governance systems. They provide guidance for reporting, environmental management, transparency, certification, and policy development, but none was specifically designed to support integrated strategic planning at the scale of MDs. Consequently, they do not simultaneously incorporate geological continuity, mining potential, territorial planning, productive diversification, infrastructure, environmental constraints, socioeconomic development, legal conditions, and governance within a unified planning model [105,108].

Table 1 summarizes the main characteristics of the principal international mining sustainability frameworks and compares them with the proposed SMD framework. The comparison highlights the principal conceptual contribution of this study: unlike previous approaches, the framework adopts the MDs as the fundamental planning unit. It integrates eleven complementary dimensions into a single territorial strategic planning framework. This gap provides the conceptual rationale for the multidimensional framework proposed in this study.

Table 1. Comparison of major international mining sustainability frameworks and the proposed SMD framework.

Framework	Year	Primary Objective	Unit of Analysis	Main Focus	Geological Integration	Territorial Planning	Productive Diversification
ICMM	2003	Responsible mining	Company	Principles	No	Partial	No
TSM	2004	Operational sustainability	Operation	Performance	No	Partial	No
FRM	2005	Responsible mining	Project	Best practices	No	No	No
SUSOP®	2010	Sustainable mine design	Project	Early-stage sustainability	Partial	Partial	No
LPSPD	2011	Sustainable projects	Project	Life cycle	No	Partial	No
MPF	2013	Mining policy	National sector	Governance	No	Partial	Partial
IRMA	2018	Responsible mining certification	Operation	Certification	No	Partial	No
EITI	2023	Transparency	National sector	Disclosure	No	No	No
GRI 14	2024	Sustainability reporting	Company	ESG reporting	No	Partial	No
Proposed SMD framework	2026	Strategic district planning	Mining district	Integrated territorial planning	Yes	Yes	Yes

3. Methodology

This study adopted an exploratory, conceptual research design to develop a multidimensional framework for SMDs. Rather than proposing a new analytical methodology or empirically validating an existing model, the research synthesized complementary

sources of scientific, institutional, and territorial evidence to identify the key dimensions that characterize SMDs.

To achieve this objective, the study combined bibliometric, institutional, and geospatial analyses to establish the conceptual and territorial foundations of the proposed framework. Bibliometric analysis was selected to systematically identify the principal research themes, knowledge gaps, and conceptual relationships within the scientific literature. Institutional analysis and process tracing were employed to examine the evolution of mining policies, governance arrangements, and regulatory frameworks. In contrast, geospatial analysis incorporated the spatial distribution of mineral resources, mining activities, territorial constraints, and strategic infrastructure into the territorial planning perspective. The integration of these complementary methods supported the development of both the multidimensional conceptual framework and a set of illustrative and hypothetical KPIs for strategic planning and governance of SMDs.

The methodological workflow comprised four sequential stages:

1. Systematic literature review and bibliometric analysis, to identify the principal research trends, thematic clusters, and knowledge gaps related to MDs, sustainable mining, sustainability, planning, governance, mineral economics, and cluster theory.
2. Institutional and regulatory analysis, to examine the evolution of mining policies, governance instruments, and institutional arrangements relevant to MDs through document analysis and process tracing.
3. Geospatial characterization of mining territories, to incorporate the spatial distribution of mineral resources, mining rights, DMs, environmental and social constraints, land-use restrictions, protected areas, and strategic infrastructure into the conceptual framework.
4. Development of the multidimensional conceptual framework and hypothetical KPIs, integrating the evidence generated during the previous stages into a coherent conceptual model for SMDs.

These stages are summarized in Figure 2.

Accordingly, this framework should be understood as a conceptual planning model intended to support future empirical applications, rather than as a predictive or validated analytical tool.

3.1. Bibliometric Protocol

3.1.1. Scientific Databases and Search Strategy

A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Scientific information was retrieved from the databases:

1. ScienceDirect;
2. Scopus;
3. Web of Science.

These databases were selected for their broad coverage of geosciences, mining engineering, mineral economics, environmental sciences, sustainability studies, and public policy research, and for the fact that their simultaneous use reduces database-specific bias and improves the literature coverage.

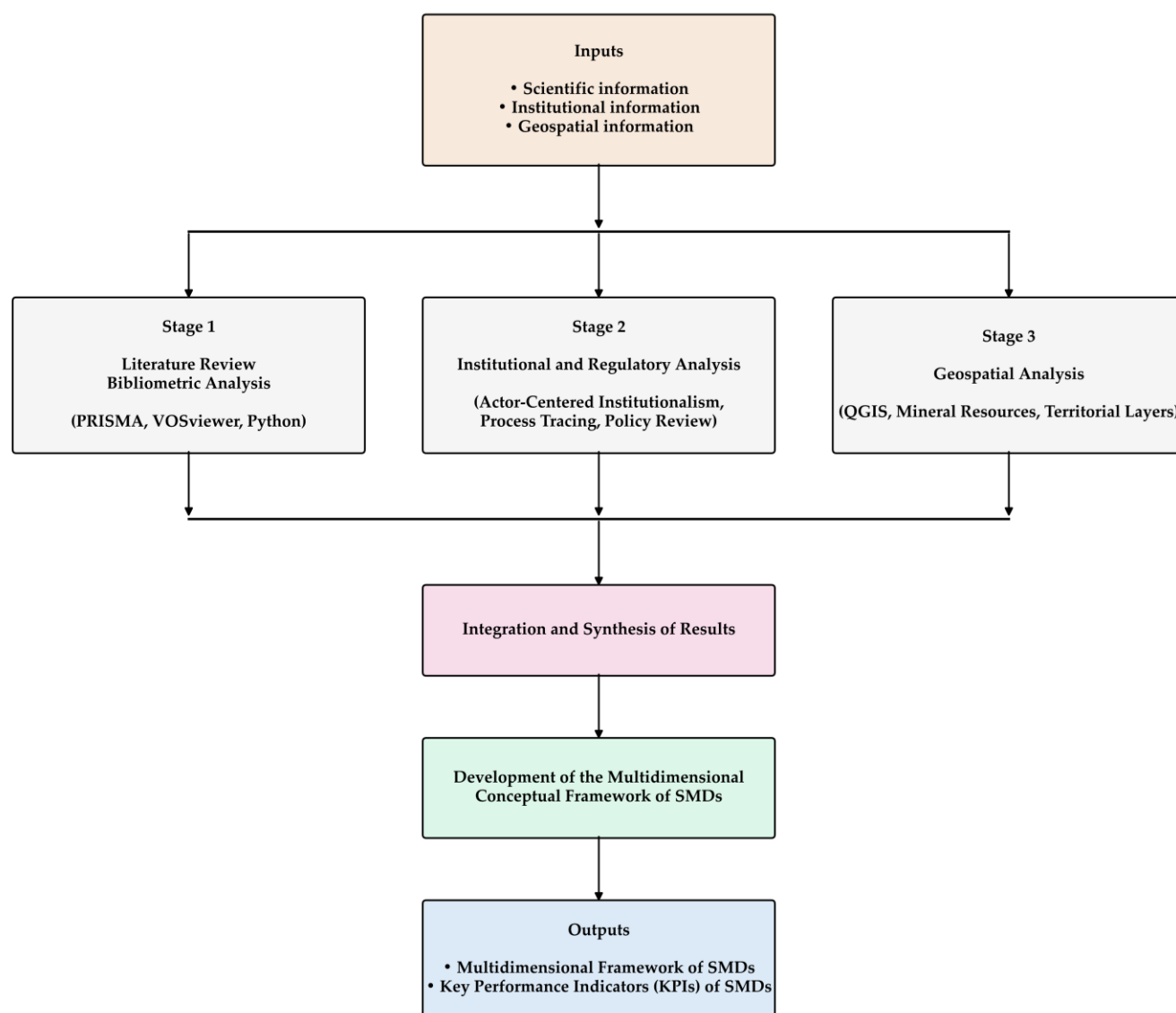


Figure 2. Methodological workflow for the development of the SMD framework. Developed by the authors based on the proposed research methodology.

The analysis period was restricted to publications from 2014 to 2026 to capture recent developments in sustainable mining, territorial governance, and MD planning. To maximize retrieval and reduce keyword bias, the review employed several Boolean combinations incorporating the study’s principal concepts. Equation 1 shows the principal Boolean search equation.

$$\text{“mining district” AND (sustainable mining OR sustainability OR planning OR governance OR mineral economics OR cluster theory)} \quad (1)$$

To assess the novelty of the proposed concept, two complementary searches were performed using the exact expressions in Equations (2) and (3).

$$\text{“sustainable mining district”} \quad (2)$$

$$\text{“mining district planning”} \quad (3)$$

No indexed publications explicitly employed the expressions “sustainable mining district” or “mining district planning”, indicating that the concept of SMDs has not yet been formally conceptualized in the scientific literature. This finding provides preliminary evidence of the conceptual originality of the proposed framework and reveals a gap between existing research on MDs and current sustainability-oriented planning approaches.

Consequently, this study seeks to bridge that gap by proposing a multidimensional conceptual framework specifically designed for the strategic planning and governance of SMDs.

3.1.2. PRISMA Screening Procedure

The literature search followed the PRISMA 2020 framework to ensure transparency and reproducibility of the identification process (Figure 3). Records retrieved from ScienceDirect, Scopus, and Web of Science were exported in RIS format and merged into a single bibliographic database using Mendeley Reference Manager (version 2.143.0).

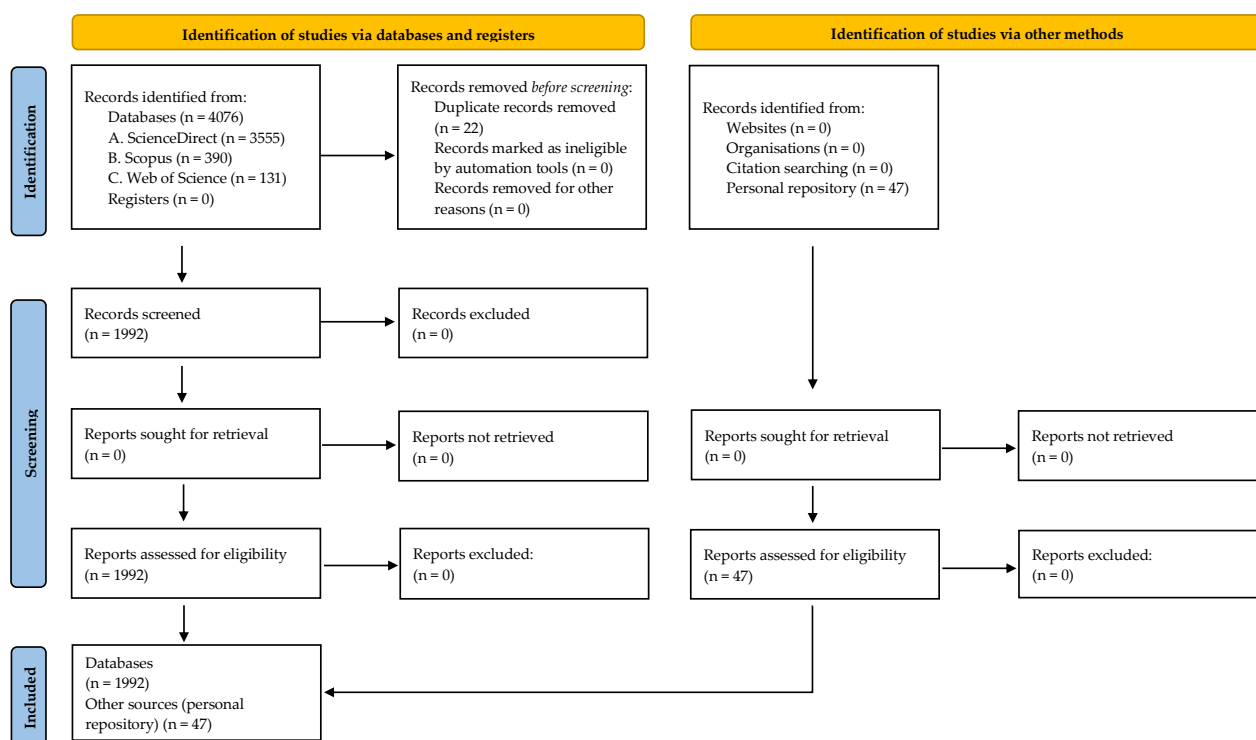


Figure 3. PRISMA flow diagram of the literature review process. Adapted by the authors from the PRISMA 2020 flow diagram for systematic reviews.

Duplicate records were identified through DOI matching, title comparison, and manual verification. After duplicates were removed, all remaining unique records were retained for bibliometric analysis. Unlike conventional systematic reviews, the objective of this study was not to identify a reduced set of studies addressing a narrowly defined research question, but to characterize the entire body of indexed scientific literature related to MDs and their associated sustainability dimensions. Consequently, no additional records were excluded after the duplicate-removal stage because every unique publication contributed to the bibliometric mapping of the research field.

Accordingly, the PRISMA workflow in this study documents the construction of the bibliographic dataset rather than the selection of evidence for quantitative synthesis. The complete corpus was subsequently analyzed using VOSviewer (version 1.6.20) and Python (version 3.8.20) to generate keyword co-occurrence networks, temporal evolution analyses, country collaboration networks, and thematic structures.

Although all retrieved records were retained for bibliometric processing, the qualitative interpretation of the literature was more selective. Publications directly addressing MDs, sustainable mining, governance, and strategic planning were examined in greater depth to support the conceptual development of the proposed SMD framework.

Therefore, the inclusion criteria guided the narrative synthesis and conceptual interpretation rather than the bibliometric dataset itself.

This application of PRISMA is consistent with bibliometric review studies, in which comprehensive literature coverage is prioritized over study exclusion to minimize selection bias in knowledge mapping.

3.1.3. Bibliometric Material and Data Processing

Bibliometric processing was performed using VOSviewer (version 1.6.20) and Python implemented in Jupyter Notebook (version 6.1.4). The merged RIS database contained bibliographic metadata, including titles, abstracts, authors, author keywords, index keywords, and cited references. The consolidated dataset contained 2017 registers with 5277 keywords.

To identify robust thematic structures while reducing terminological noise, the minimum keyword occurrence threshold was established through an iterative calibration process rather than being arbitrarily selected. The threshold was progressively adjusted to obtain a bibliometric network containing approximately 100–150 keywords, a range considered suitable for preserving thematic diversity while ensuring interpretability. Sensitivity analyses were performed using minimum occurrence thresholds of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, and 40. Figure 4 shows the threshold selection for keyword co-occurrence analysis.

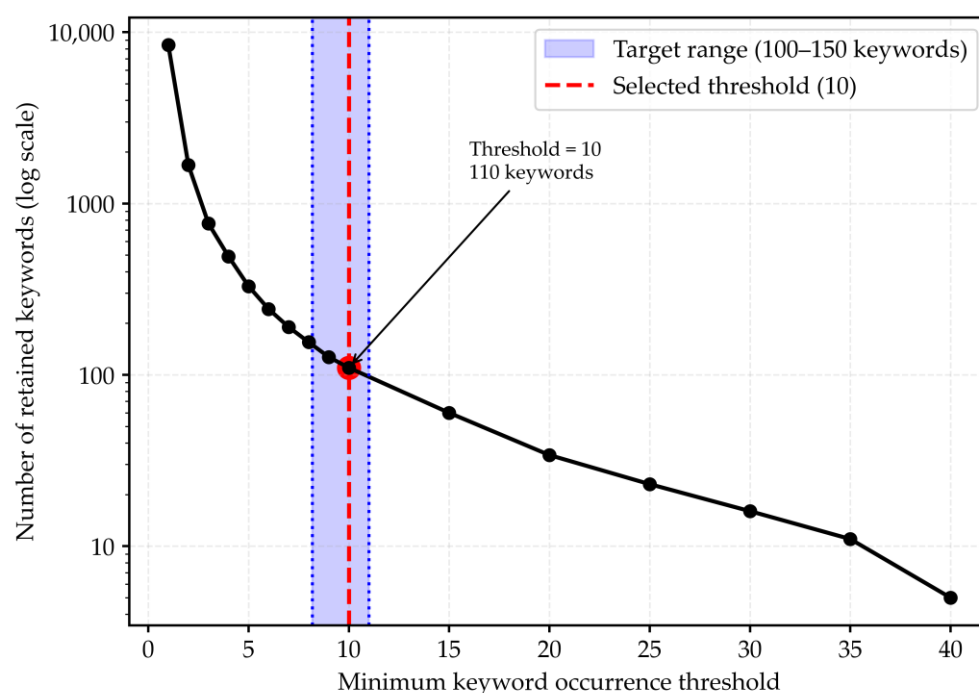


Figure 4. Threshold selection for keyword co-occurrence analysis. Prepared by the authors using Python (Jupyter Notebook).

A threshold of 10 occurrences yielded a network of 110 keywords, providing the best compromise among thematic coverage, network complexity, and visualization clarity. Lower thresholds produced highly fragmented, visually dense networks dominated by infrequent terms, whereas higher thresholds excluded many relevant concepts and reduced thematic representativeness. Consequently, the threshold of 10 occurrences was adopted for the subsequent keyword co-occurrence analysis.

3.1.4. Construction of Conceptual and Graphical Frameworks

The conceptual framework and the accompanying graphical representations were developed in Python using Jupyter Notebook (the complete source code is provided in the Supplementary Material). These visualizations were designed to: (1) represent the interactions among the eleven planning dimensions; (2) illustrate the hierarchical organization of the framework; and (3) demonstrate how KPIs could be integrated into a multidimensional planning and monitoring system.

The radar plots were generated using normalized synthetic KPIs assigned to each planning dimension exclusively for visualization purposes. The normalization procedure transformed illustrative values with different measurement scales into a common dimensionless range, allowing direct graphical comparison among heterogeneous indicators. These values are entirely hypothetical and do not originate from empirical observations, case studies, or measured performance data. Consequently, the radar diagrams should not be interpreted as validation results or as an assessment of the sustainability performance of any district.

Instead, the graphical examples serve solely to illustrate the potential operationalization of the proposed conceptual framework and to demonstrate how future empirical applications could integrate multidimensional indicators into a unified decision-support and monitoring tool. The empirical definition, calibration, weighting, and validation of KPIs are beyond the scope of this study and constitute an important direction for future research.

3.1.5. Complementary Institutional Sources

To integrate the regulatory and institutional dimensions, official information was compiled from:

1. The National Mining Agency (ANM);
2. The Colombian Geological Survey (SGC);
3. The Ministry of Mines and Energy;
4. The National Planning Department (DNP);
5. The Mining and Energy Planning Unit (UPME);
6. Law 685 of 2001;
7. Law 2294 of 2023;
8. Decree 0977 of 2024;
9. CONPES 4129 of 2023;
10. The National Mining Development Plan 2024–2035.

These sources provided up-to-date information on mining rights, mineral resources, MD delimitations, and the institutional framework that supports mining governance.

3.2. Institutional Analysis

This study adopted a qualitative institutional approach based on:

1. Actor-Centered Institutionalism (ACI);
2. Process tracing.

The objective was to reconstruct the regulatory and institutional processes associated with the creation of SMDPDs in Colombia and to identify the actors, incentives, and governance mechanisms that shape their implementation.

3.2.1. Actor-Centered Institutionalism

The analytical framework is based on ACI, which assumes that public policy outcomes emerge from strategic interactions among actors operating under formal and informal institutional constraints [142,143].

Under this perspective, the creation of SMDPDs is interpreted as the result of dynamic interactions among:

1. National government institutions;
2. Regional authorities;
3. Mining organizations;
4. Local communities;
5. Regulatory agencies.

The ACI framework facilitated the analysis of:

6. Actor constellations;
7. Modes of interaction;
8. Institutional incentives;
9. Regulatory arrangements.

3.2.2. Process Tracing

To operationalize the ACI framework, process tracing methodology was applied to reconstruct the sequence of regulatory and administrative events that led to the establishment of SMDPDs [144].

The analysis examined:

1. Article 231 of Law 2294 of 2023;
2. Decree 0977 of 2024;
3. CONPES 4129 of 2023;
4. The National Mining Development Plan 2024–2035;
5. Resolution 40,436 of 18 October 2024;
6. The Agreement for the Formalization and Regularization of Small and Medium-Scale Mining.

This procedure provided institutional traceability and strengthened the evidence chain linking policy formulation and territorial implementation.

3.3. Geospatial Methodology

Geospatial analysis and map creation were performed using QGIS Desktop (version 3.8.1—Zanzibar), an open-source tool widely used in mining, environmental, and land-use planning studies. The MAGNA—SIRGAS reference system (EPSG:4686) was used as the official cartographic framework. The shapefiles were obtained from:

1. SGC;
2. ANM;
3. official territorial planning databases.

The shapefiles are provided in the Supplementary Materials. The principal GIS layers included:

1. Geology at scales of 1:100,000 and 1:500,000;
2. Mineral occurrences;
3. Metallogenic districts;
4. Mining rights and applications;
5. Protected areas;
6. Administrative boundaries;
7. Transportation infrastructure.

The geospatial workflow consisted of:

1. Compilation and harmonization of spatial layers;
2. Overlay analysis;
3. Identification of multidimensional elements planning;
4. Assessment of territorial coherence.

The analysis integrated geological, mining, environmental, social, infrastructural, legal, and governance factors that influence mineral resource development.

Because district boundaries are inherently dynamic and depend on evolving geological and socioeconomic conditions, the resulting delimitations should be interpreted as planning-support boundaries rather than fixed administrative units. Coordinate uncertainties associated with source datasets and differences in mapping scales constitute limitations that should be considered in future applications of the framework.

3.4. Integration of Institutional and Territorial Analyses

The integration of institutional and geospatial analyses enabled the examination of how actor constellations and governance mechanisms operate within territories characterized by high mining intensity and varying degrees of formality.

The case of the Bajo Cauca District illustrates how geological characteristics, mining concentration, and institutional arrangements interact to shape incentives for:

1. Mining formalization;
2. Gold traceability;
3. Productive diversification;
4. Territorial governance.

Consequently, the proposed methodology links institutional and territorial dimensions and provides a conceptual framework for the strategic planning and governance of SMDs in Colombia and other mineral-rich regions.

4. Results

4.1. Bibliometric Findings

The bibliometric analysis provides an overview of the scientific evolution of research related to MDs, sustainable mining, territorial planning, and governance. By combining temporal trends, keyword co-occurrence networks, and country-level scientific production, the analysis identifies the principal research themes, their evolution over time, and the emerging knowledge domains that support the conceptual development of SMDs.

Figure 5 illustrates the temporal evolution of the keyword co-occurrence network. The results reveal a clear transition from earlier studies that predominantly focused on mining impacts, mine waste, pollution control, and environmental assessment toward more recent research that emphasizes the circular economy, critical minerals, and the energy transition. This evolution reflects the progressive expansion of mining research from operational and environmental concerns to integrated territorial and sustainability-oriented planning approaches.

To complement the network analysis, a Pareto assessment (Figure 6) of keyword frequencies was conducted to identify the concepts that account for the largest proportion of the scientific literature. The results indicate that a relatively large number of recurring terms account for a substantial share of publications, highlighting the thematic consolidation of several research domains while also revealing opportunities for emerging concepts.

Geographically, China exhibits the highest publication output, followed by Ghana, Colombia, Peru, and India, indicating that scientific production is concentrated in countries where mining is a major economic activity and where resource governance and environmental management have become important research priorities. Together, these thematic and geographical patterns highlight the growing integration of sustainability into mining research and reinforce the need for comprehensive territorial planning approaches such as the SMD framework proposed in this study.

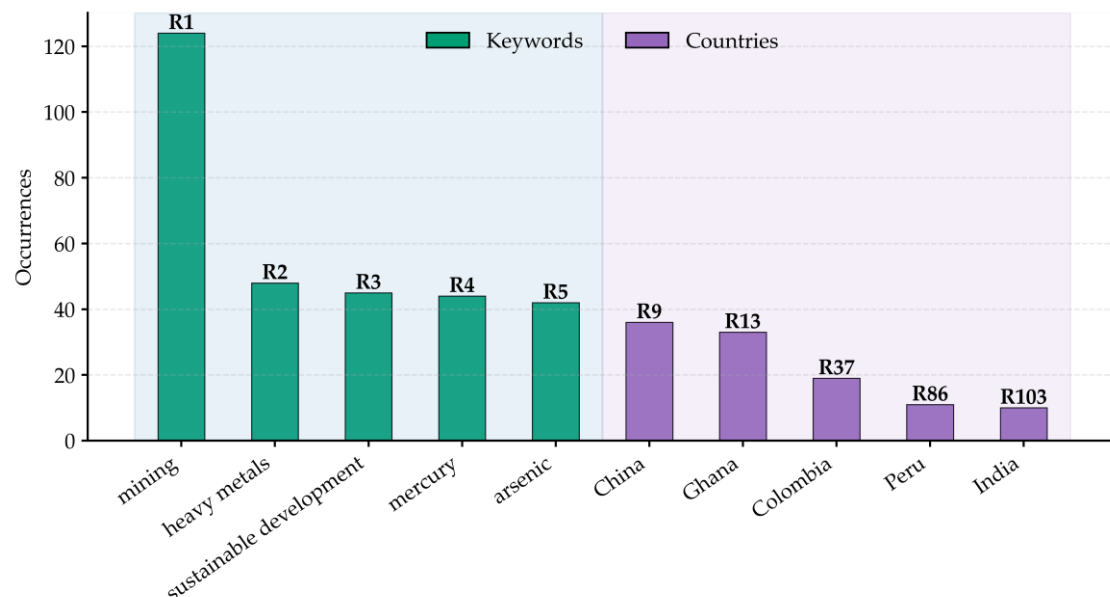


Figure 7. Top 5 Keywords and Countries. Prepared by the authors using Python (Jupyter Notebook).

4.2. Institutional Findings

The institutional analysis revealed a significant evolution in the concept of MDs in Colombia. Originally adopted from the definition proposed by the U.S. Bureau of Mines, MDs were primarily understood as geographically defined areas containing mineral resources under a common mining tradition [145]. Recent regulatory reforms have substantially expanded this concept, transforming MDs into SMDPDs, which integrate mining development with territorial planning, environmental management, productive diversification, and institutional coordination [146].

Process tracing identified Article 231 of Law 2294 of 2023 as the critical institutional event that formally introduced SMDPDs into the Colombian mining policy framework. Subsequent regulations, including Decree 0977 of 2024, CONPES 4129 of 2023, and the National Mining Development Plan 2024–2035, progressively operationalized this policy by defining territorial criteria, governance mechanisms, and implementation instruments. Together, these regulatory milestones constitute the institutional sequence through which MDs evolved from descriptive geological entities into integrated territorial governance instruments.

The institutional analysis identified two major categories of SMDPDs currently proposed by the Ministry of Mines and Energy (Table 2). The first group comprises formalization districts, primarily located in regions characterized by extensive small-scale and informal gold mining. The second group corresponds to large-scale mining and reindustrialization districts designed to strengthen mineral value chains and promote productive diversification.

Table 2. Projection of SMDPDs in Colombia.

Category	District	Municipalities	Department
A. SMDPDs to Mining Formalization	1. Bajo Cauca District	Caucasia, Caceres, Zaragoza, Taraza, El Bagre, and Nechi	Antioquia
	2. Telembi Triangle District	Barbacoas, Magui, and Roberto Payan	Nariño
	3. Foothills and Nariño Mountain Range District, Abades	Santa Cruz, Samaniego, La Llanada, Mal-lama, and Los Andes Sotomayor	Nariño
	4. Northwest Nariño District	Iscuande and El Charco	Nariño
	5. Cauca Pacific Coast District	Guapi, Timbiquia, and Lopez de Micay	Cauca
	6. Northern Cauca District	Suarez and Buenos Aires	Cauca
	7. Alto Atrato District	Bagado, Lloro, Atrato (Yuto), and Certe-gui	Choco
B. SMDPDs to Large-Scale Mining and Reindustrialization	1. Cesar Life District	El Paso, La Jagua de Ibirico, and Becerril	Cesar
	2. Carbon generation hubs of the country	Under definition	La Guajira, Norte de Santander, Boyaca, and Cundinamarca

The spatial distribution of the proposed districts demonstrates a clear institutional prioritization of territories historically affected by informal gold mining, particularly in Antioquia, Choco, Cauca, and Nariño. These regions combine high mineral potential with persistent governance challenges, including informality, environmental degradation, and conflicts associated with mineral extraction. Consequently, the initial implementation of the SMDPDs policy focuses primarily on formalization processes and strengthening institutional capacity before expanding to broader regional development objectives.

From an ACI perspective, the implementation of SMDPDs involves the interaction of multiple actors operating under different institutional incentives. National government agencies are responsible for regulatory design and territorial delimitation, whereas regional governments, mining organizations, local communities, and environmental authorities participate in negotiation, implementation, and conflict management. Rather than being purely administrative reforms, SMDPDs emerge as governance arrangements in which constellations of actors determine policy implementation across heterogeneous mining territories.

The causal sequence reconstructed through process tracing is summarized in Table 3, which links the principal institutional actors to the successive regulatory milestones that led to the implementation of the first of these SMDPDs, namely the Bajo Cauca District. The reconstructed evidence chain indicates that the establishment of SMDPDs did not result from a single legislative decision but from a cumulative institutional process involving successive regulatory instruments, planning documents, administrative resolutions, and stakeholder negotiations. This sequence illustrates how institutional change gradually translated national policy objectives into territorial implementation mechanisms.

Table 3. Articulation of the ACI approach and the process tracing methodology.

Actor-Centered Institutionalism	Process Tracing	Regulation/Agreement
Informal Gold Mining	Congress	Law 2294 of 2023. National Development Plan 2022–2026.
	Congress	Article 231 of Law 2294 of 2023. Creation of SMDPDs.
	Ministry of Mines and Energy	Decree 0977 of 2024. Regulating Article 231 of Law 2294 of 2023.

	National Planning Department (DNP) National Council for Economic and Social Policy (CONPES)	CONPES 4129 of 2023. National Reindustrialization Policy.
Institutional Framework and Policy Environment	Ministry of Mines and Energy Mining and Energy Planning Unit (UPME)	National Mining Development Plan 2024–2035.
Actor	Ministry of Mines and Energy Mining and Energy Planning Unit (UPME)	Diagnosis of the Bajo Cauca District for Productive Diversification. 2024.
	Ministry of Mines and Energy	Formalization of the first of the SMDPDs in the Bajo Cauca Region of Antioquia. Resolution 40,436 of 18 October 2024.
Constellation of Actors	National Mining Coordinator Leaders and representatives of regional mining groups	Mining strike in the Bajo Cauca Region of Antioquia. 21–26 October 2024.
Modes of Interaction	Representatives of the National Government	
	Representatives of Local Governments Office of the Attorney General	Mining strike in the Bajo Cauca Region of Antioquia. 21–26 October 2024.
Formalization of Gold Mining	Office of the Ombudsman National Mining Coordinator	

4.3. Geospatial Findings

The Bajo Cauca Agro-Mining and Fishing District was selected as an illustrative case study because it constitutes the first of the SMDPDs currently undergoing formal implementation by the Colombian government. Covering approximately 811,684 ha and encompassing the municipalities of Taraza, Caceres, Caucasia, Nechi, El Bagre, and Zaragoza, the district provides an appropriate example for evaluating the spatial coherence between geological conditions, mining activity, environmental constraints, and territorial governance. Figure 8 presents the proposed district boundaries together with mining rights, administrative divisions, protected areas, and the regional hydrographic network [147].

The spatial analysis revealed three principal characteristics of the proposed district. First, mining rights and pending applications are highly concentrated within the district boundaries, confirming that the delimitation prioritizes territories with consolidated mining activity. Second, portions of the eastern sector overlap with protected areas included within the Second Law Forest Reserve, introducing environmental restrictions that require coordinated governance and integrated territorial planning. Third, the spatial continuity of mining rights follows the principal hydrographic corridors of the Cauca and Nechi rivers, reflecting the long-standing relationship between alluvial gold deposits and the region's historical mining evolution.

Although the Bajo Cauca case illustrates the application of the proposed framework at the district scale, the geospatial analysis was subsequently expanded to the national level to identify the principal territorial components required for SMD planning across Colombia. Figure 9 synthesizes the principal spatial layers considered relevant for SMD planning at the national scale. These include administrative divisions, metallogenic domains and districts, alluvial districts, mining rights, protected areas, indigenous territories, transportation infrastructure, and the national power transmission network. Together, these layers illustrate the multidimensional spatial information required to evaluate the territorial feasibility of future SMDs.

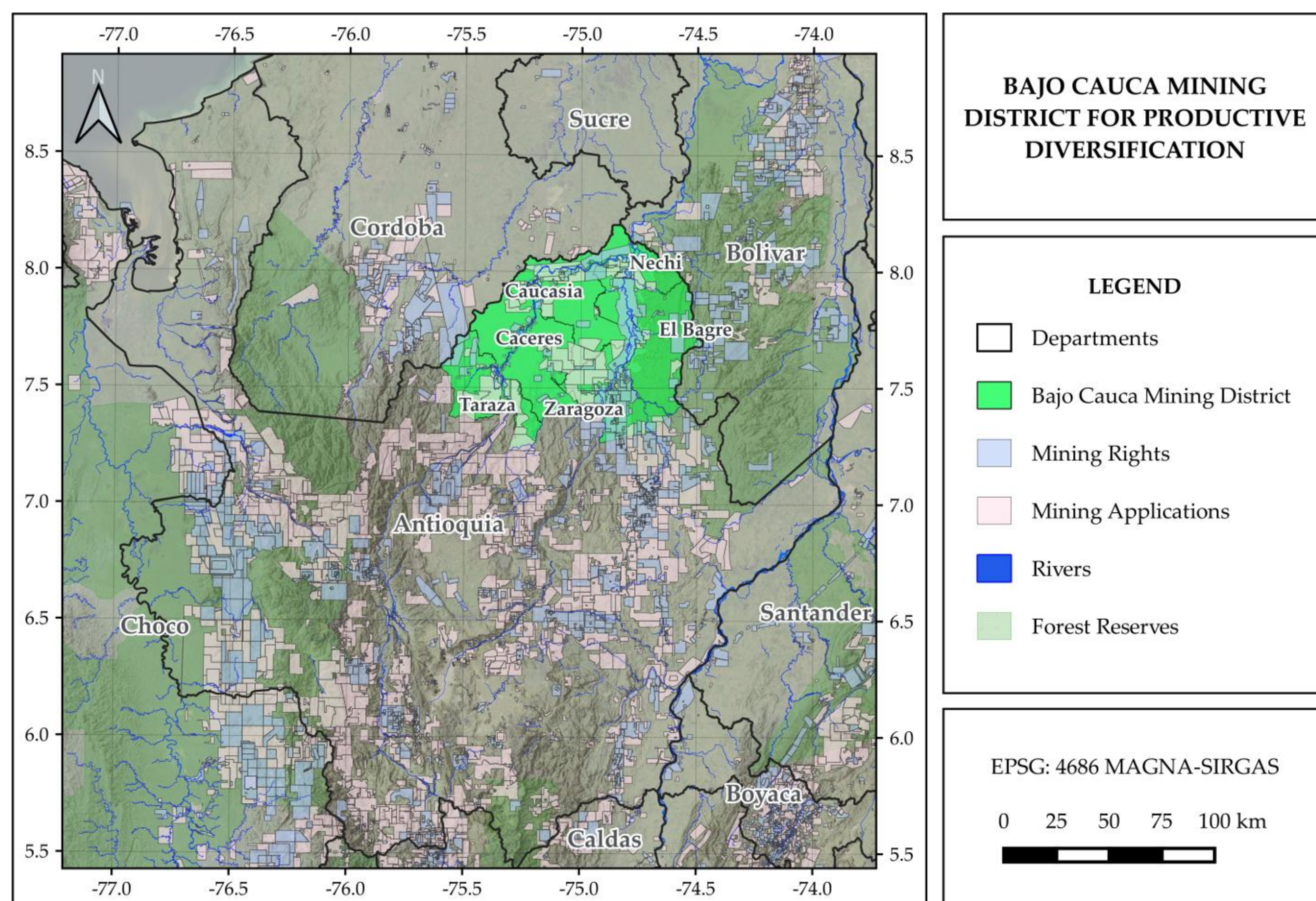


Figure 8. Map of the Bajo Cauca Mining District for Productive Diversification. Prepared by the authors using QGIS Desktop based on official geospatial datasets.

Owing to differences in spatial resolution and data density, only the principal planning layers are displayed in Figure 9. Nevertheless, the complete geospatial database integrates additional thematic information that should be incorporated into future district delimitation exercises at municipal and regional scales to ensure consistency between geological potential, mining activity, environmental protection, infrastructure availability, and socioeconomic conditions.

The importance of gold mining in consolidating SMDs in Colombia is highlighted, as it is present throughout the national territory within the Andean and Amazonian Craton metallogenic domains.

Geological data indicate that Colombia has 57 identified metallogenic districts, 43 of which are gold-bearing, accounting for 75.4% of the total. Likewise, of the 31 identified alluvial districts, 27 are exclusively gold-bearing, and 3 correspond to gold–platinum associations, equivalent to 96.8%. These results confirm that gold mineralization constitutes the structural basis upon which most territories susceptible to consolidation as SMDs are configured. Furthermore, the Bajo Cauca District is gold-bearing and primarily alluvial.

A key finding of the analysis is that most of the prioritized districts have a higher density of mining rights than other territories with similar geological potential. This suggests that district planning has prioritized areas with established mining activity, rather than emerging prospective areas.

Additionally, 10 metallogenic districts associated with copper ore were identified. These are spatially concentrated along the Andes Mountains and represent 17.5% of the total metallogenic districts identified in the country, making them the second most common type of district. This distribution demonstrates a direct relationship between Andean

geology and the formation of mineralized systems, such as porphyry copper deposits, skarns, and hydrothermal veins, which constitute the main global source of copper. The concentration of these districts in the Colombian Andes suggests significant—yet largely untapped—mineral wealth, especially compared with other Andean countries such as Chile and Peru, where copper has become a strategic mineral for economic development and integration into global value chains. From a strategic perspective, these copper districts acquire structural relevance in the context of the global energy transition.

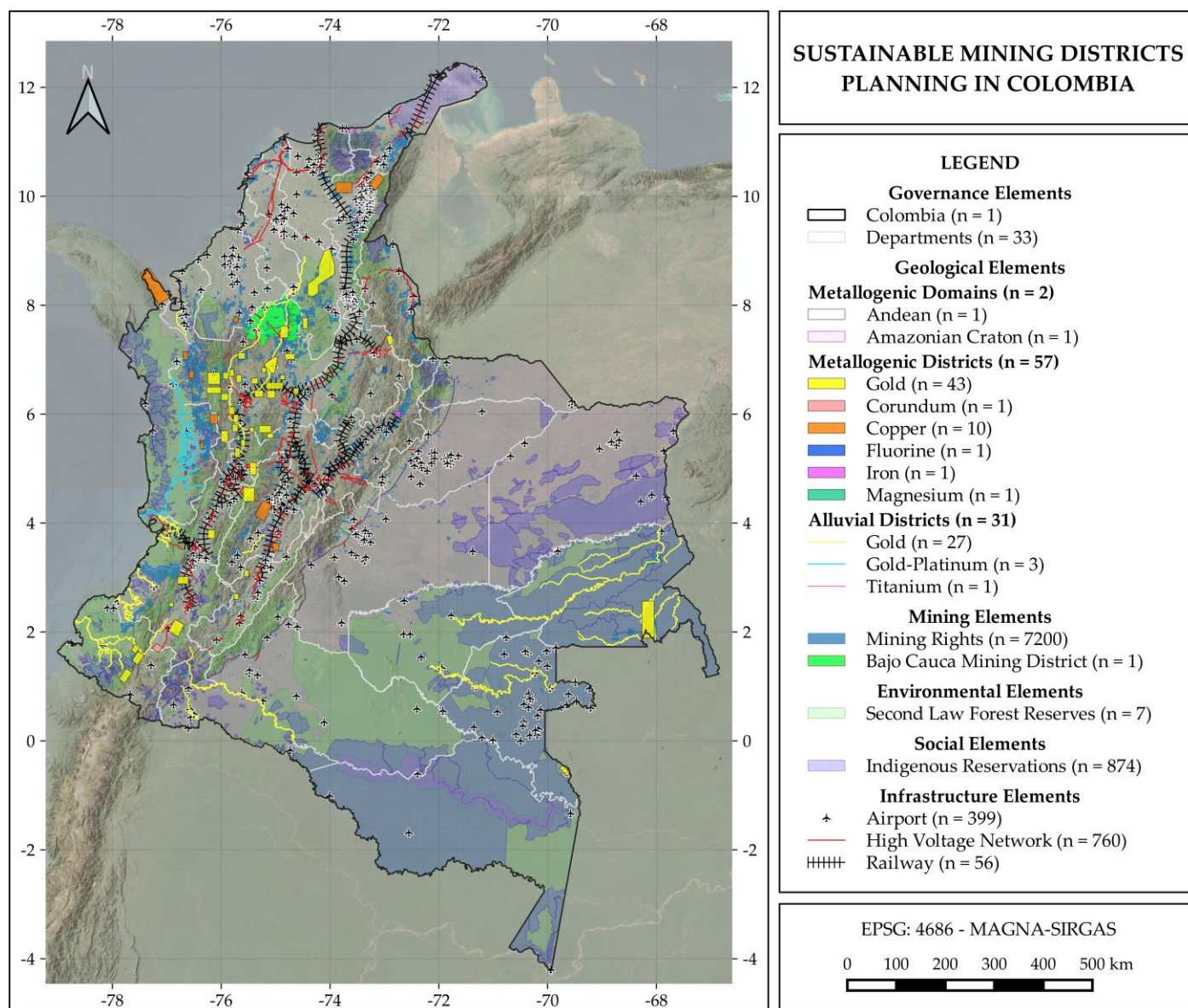


Figure 9. Map of SMD planning elements in Colombia. Prepared by the authors using QGIS Desktop based on official geospatial datasets.

Overall, the geospatial assessment demonstrates that SMD planning cannot rely solely on mineral concentration. Instead, effective district delimitation requires integrating geological, environmental, institutional, infrastructural, legal, and socioeconomic information. These findings reinforce the framework's multidimensional structure and provide territorial evidence supporting its practical implementation.

4.4. Framework Development

The findings derived from the bibliometric, institutional, and geospatial analyses were synthesized into an integrated conceptual framework for SMDs. Rather than representing independent analytical components, these three lines of evidence converge to define the planning dimensions, governance structure, and KPIs required to implement SMDs in line with sustainability principles.

Figure 10 presents the hierarchical organization of the proposed multidimensional conceptual framework. The model structures the eleven planning dimensions and the one hundred key elements within an integrated territorial planning system.

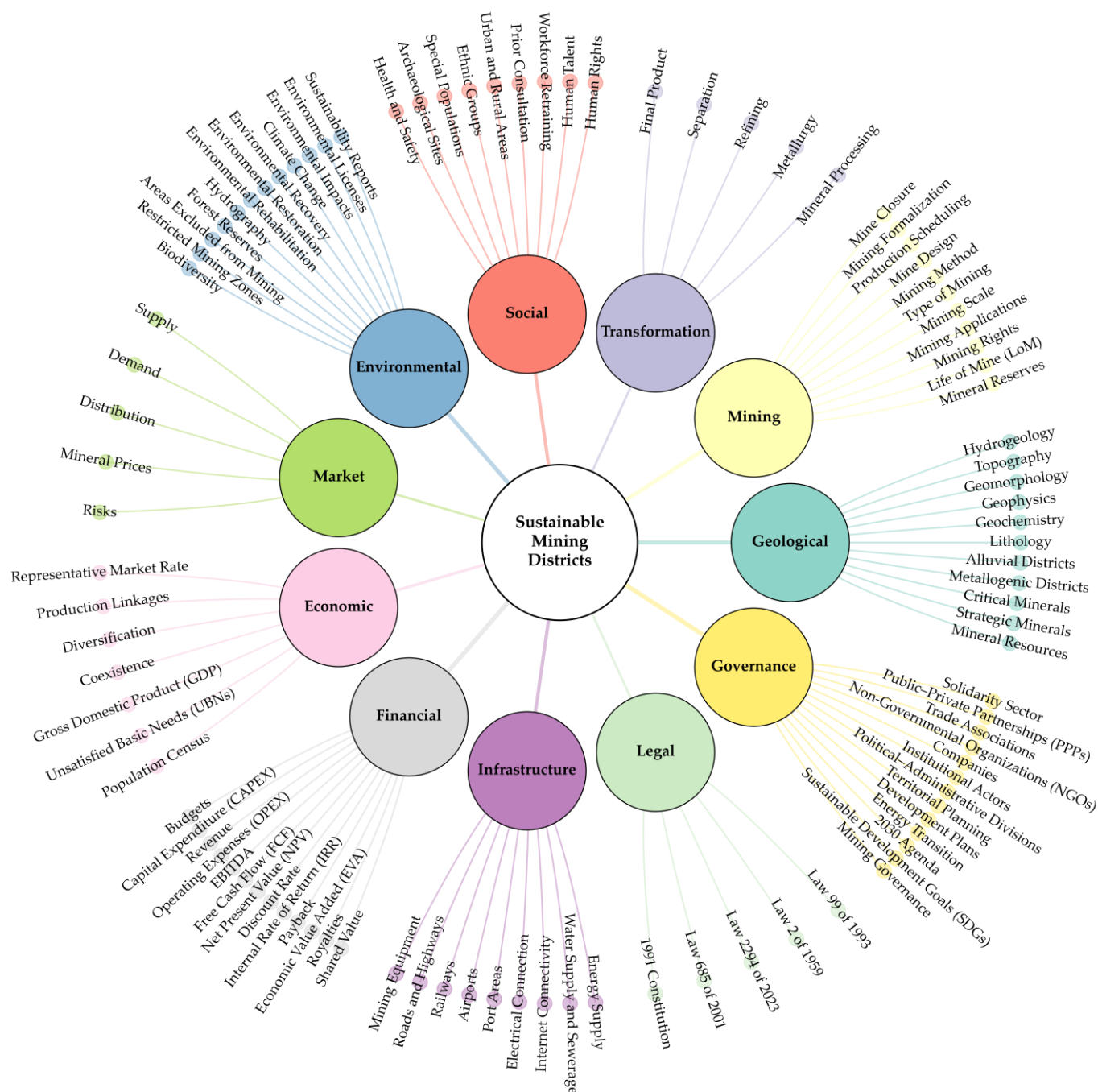


Figure 10. Hierarchical framework of SMDs. Developed by the authors based on the proposed conceptual framework and generated using Python (Jupyter Notebook).

To operationalize the framework, each planning element was associated with illustrative KPIs, along with their measurement units, potential data sources, and recommended monitoring frequencies (Table 4). This structure transforms the conceptual framework into an operational planning tool that supports monitoring, evaluation, and evidence-based decision-making. To demonstrate the practical applicability of the framework, all KPIs were transformed into normalized synthetic values and represented using a multidimensional radar diagram (Figure 11). The normalization procedure enables variables with different units and scales to be visualized in a common analytical space, thereby allowing the various planning dimensions to be evaluated simultaneously. The values shown are purely illustrative and do not represent measurements from a real district.

Collectively, the framework synthesizes the bibliometric evidence, institutional analysis, and geospatial assessment into an integrated planning model for SMDs. Beyond its conceptual contribution, the framework provides an operational structure that can support district delimitation, strategic planning, performance monitoring, and policy evaluation. Although the radar diagram uses normalized synthetic values for illustrative purposes, the proposed KPI system is designed to incorporate empirical indicators derived from official datasets, thereby facilitating future implementation and validation under real-world territorial conditions.

Table 4. KPIs of SMDs, measuring unit, data source, and monitoring frequency.

Dimension	Element	Key Performance Indicator (KPI)	No. KPI	Measurement Unit	Data Source	Monitoring Frequency
Geological	Mineral Resources	Measured, indicated, and inferred mineral resources	KPI1	Mt	JORC, NI 43-101 technical reports, Company technical reports	Annual
Geological	Strategic Minerals	Number of strategic minerals identified	KPI2	No. strategic minerals	National mineral inventories	Annual
Geological	Critical Minerals	Number of critical minerals identified	KPI3	No. critical minerals	Critical minerals strategies and inventories	Annual
Geological	Metallogenic Districts	Mineral prospectivity index	KPI4	Index (0–1)	GIS analysis and prospectivity studies	Every 5 years
Geological	Alluvial Districts	Area of alluvial deposits	KPI5	km ²	Geological mapping and remote sensing	Every 5 years
Geological	Lithology	Lithological diversity index	KPI6	No. lithological units	Geological maps	Every 5 years
Geological	Geochemistry	Geochemical anomaly density	KPI7	anomalies/km ²	Geochemical surveys	Every 5 years
Geological	Geophysics	Geophysical survey coverage	KPI8	% area	Geophysical campaigns	Every 5 years
Geological	Geomorphology	Geomorphological units mapped	KPI9	No. geomorphological units	Geomorphological studies	Every 5 years
Geological	Topography	Average terrain slope	KPI10	%	Digital elevation models (DEM)	Every 5 years
Geological	Hydrogeology	Groundwater availability index	KPI11	m ³ /year	Hydrogeological studies	Annual
Mining	Mineral Reserves	Proven and probable mineral reserves	KPI12	Mt	JORC, NI 43-101 technical reports, Company technical reports	Annual
Mining	Life of Mine (LoM)	Estimated mine life	KPI13	Years	Mine planning reports	Annual
Mining	Mining Rights	Granted mining rights	KPI14	No. mining rights	Mining authority databases	Annual
Mining	Mining Applications	Pending mining applications	KPI15	No. mining applications	Mining authority databases	Annual
Mining	Mining Scale	Average annual production	KPI16	t/year	Production reports	Annual
Mining	Type of Mining	Formal mining operations	KPI17	%	Mining census	Annual
Mining	Mining Method	Mechanized mining operations	KPI18	%	Company technical reports	Annual
Mining	Mine Design	Projects with mine plans approved	KPI19	%	Mining authority	Annual
Mining	Production Scheduling	Production plan compliance	KPI20	%	Company production reports	Annual
Mining	Mining Formalization	Formalized miners	KPI21	%	Mining authority databases	Annual

Mining Transformation	Mine Closure	Approved closure plans	KPI22	%	Environmental authorities	Annual
	Mineral Processing	Processing capacity	KPI23	t/day	Processing plant reports	Annual
Transformation	Metallurgy	Metal recovery	KPI24	%	Metallurgical reports	Annual
Transformation	Refining	Refining capacity	KPI25	t/year	Refinery reports	Annual
Transformation	Separation	Concentrate grade	KPI26	%	Laboratory assays	Annual
Transformation	Final Product	Value-added products	KPI27	No. products	Industrial production reports	Annual
Social	Human Rights	Human rights incidents	KPI28	incidents/year	Government reports, and company ESG reports	Annual
Social	Human Talent	Qualified workforce	KPI29	% employees	Human resources reports	Annual
Social	Workforce Retraining	Workers retrained	KPI30	persons/year	Training program reports	Annual
Social	Prior Consultation	Consultations completed	KPI31	%	Government consultation reports	Annual
Social	Urban and Rural Areas	Population benefiting	KPI32	Inhabitants	Population census	Every census period
Social	Ethnic Groups	Ethnic participation	KPI33	%	Prior consultation records	Annual
Social	Special Populations	Vulnerable groups included	KPI34	%	Social development agencies	Annual
Social	Archaeological Sites	Protected heritage sites	KPI35	No. sites	Cultural heritage inventories	Every 5 years
Social	Health and Safety	Lost Time Injury Frequency Rate	KPI36	injuries/million hours	Occupational safety reports	Annual
Environmental	Sustainability Reports	Companies issuing sustainability reports	KPI37	%	ESG and sustainability reports	Annual
Environmental	Environmental Licenses	Licensed operations	KPI38	%	Environmental authority databases	Annual
Environmental	Environmental Impacts	Impact severity index	KPI39	Index	Environmental impact assessments	Annual
Environmental	Climate Change	Greenhouse gas emissions	KPI40	tCO ₂ -e/year	GHG inventories	Annual
Environmental	Environmental Recovery	Recovered area	KPI41	ha	Environmental management plans	Annual
Environmental	Environmental Restoration	Restored ecosystems	KPI42	ha	Restoration projects	Annual
Environmental	Environmental Rehabilitation	Rehabilitated area	KPI43	ha	Rehabilitation programs	Annual
Environmental	Hydrography	Water quality index	KPI44	Index	Water monitoring programs	Quarterly
Environmental	Forest Reserves	Protected forest area	KPI45	ha	Environmental authority GIS databases	Annual
Environmental	Areas Excluded from Mining	Excluded area	KPI46	km ²	Territorial planning instruments	Annual
Environmental	Restricted Mining Zones	Restricted area	KPI47	km ²	Environmental authority GIS databases	Annual
Environmental	Biodiversity	Species richness index	KPI48	Index	Biodiversity monitoring programs	Annual
Market	Supply	Mineral production	KPI49	t/year	National production statistics	Annual
Market	Demand	Domestic mineral consumption	KPI50	t/year	National consumption statistics	Annual
Market	Distribution	Export volume	KPI51	t/year	Trade statistics and customs databases	Annual
Market	Mineral Prices	Average mineral price	KPI52	USD/t	Commodity exchanges (LME, COMEX, S&P Global)	Monthly
Market	Risks	Price volatility	KPI53	%	Commodity market statistics	Monthly
Economic	Representative Market Rate	Exchange rate	KPI54	COP/USD	Central Bank statistics	Daily
Economic	Production Linkages	Local procurement	KPI55	%	Company procurement reports	Annual
Economic	Diversification	Economic diversification index	KPI56	Index	Regional economic statistics	Annual
Economic	Coexistence	Economic sectors coexisting	KPI57	No. sectors	Regional development plans	Every 4 years
Economic	Gross Domestic Product (GDP)	Mining contribution to GDP	KPI58	%	National statistics office (DANE)	Annual

Economic	Unsatisfied Basic Needs (UBNs)	Unsatisfied basic needs index	KPI59	% population	National census and socio-economic surveys	Every census period
Economic	Population Census	Population density	KPI60	inhabitants/km ²	National census	Every census period
Financial	Budgets	Annual budget	KPI61	USD/year	Company financial statements	Annual
Financial	Capital Expenditure (CAPEX)	Capital investment	KPI62	USD	Company financial statements	Annual
Financial	Revenue	Gross revenue	KPI63	USD/year	Company financial statements	Annual
Financial	Operating Expenses (OPEX)	Operating costs	KPI64	USD/year	Company financial statements	Annual
Financial	EBITDA	EBITDA margin	KPI65	%	Company financial statements	Annual
Financial	Free Cash Flow (FCF)	Free cash flow	KPI66	USD/year	Company financial statements	Annual
Financial	Net Present Value (NPV)	Net Present Value	KPI67	USD	Economic evaluation studies	Project stage updates
Financial	Discount Rate	Discount rate	KPI68	%	Economic evaluation studies	Project stage updates
Financial	Internal Rate of Return (IRR)	Internal Rate of Return	KPI69	%	Economic evaluation studies	Project stage updates
Financial	Payback	Payback period	KPI70	Years	Economic evaluation studies	Project stage updates
Financial	Economic Value Added (EVA)	Economic Value Added	KPI71	USD/year	Company financial statements	Annual
Financial	Royalties	Royalty payments	KPI72	USD/year	Government royalty reports	Annual
Financial	Shared Value	Community investment	KPI73	USD/year	Sustainability and ESG reports	Annual
Infrastructure	Mining Equipment	Equipment availability	KPI74	%	Operational reports	Annual
Infrastructure	Roads and Highways	Road density	KPI75	km/km ²	Transport infrastructure databases	Every 4 years
Infrastructure	Railways	Railway connectivity	KPI76	km	National transport infrastructure databases	Every 4 years
Infrastructure	Airports	Distance to airport	KPI77	km	GIS and transport databases	Every 4 years
Infrastructure	Port Areas	Distance to port	KPI78	km	GIS and transport databases	Every 4 years
Infrastructure	Electrical Connection	Electrification coverage	KPI79	%	Utility companies and census data	Annual
Infrastructure	Internet Connectivity	Broadband coverage	KPI80	%	Telecommunications authority statistics	Annual
Infrastructure	Water Supply and Sewerage	Population with access to water and sanitation	KPI81	% population	Utility companies and census data	Annual
Infrastructure	Energy Supply	Energy reliability	KPI82	hours/year outage	Utility companies	Annual
Legal	1991 Constitution	Constitutional compliance	KPI83	%	Legal compliance audits	Annual
Legal	Law 685 of 2001	Mining code compliance	KPI84	%	Mining authority reports	Annual
Legal	Law 2294 of 2023	Alignment with National Development Plan	KPI85	%	Government planning reports	Every 4 years
Legal	Law 2 of 1959	Forest reserve compliance	KPI86	%	Environmental authority reports	Annual
Legal	Law 99 of 1993	Environmental compliance	KPI87	%	Environmental audits	Annual
Governance	Mining Governance	Governance index	KPI88	Index	Governance assessments and surveys	Annual
Governance	Sustainable Development Goals (SDGs)	SDGs addressed	KPI89	No. SDGs	Sustainability reports	Annual
Governance	2030 Agenda	SDG targets aligned	KPI90	%	Sustainability reports and planning instruments	Annual
Governance	Energy Transition	Contribution of critical minerals to energy transition	KPI91	%	National energy and mining statistics	Annual
Governance	Development Plans	Development plans incorporating mining	KPI92	%	Municipal and regional development plans	Every 4 years
Governance	Territorial Planning	Municipal land-use plans updated	KPI93	%	Territorial planning instruments	Every 12 years
Governance	Political-Administrative Divisions	Inter-institutional coordination agreements	KPI94	No. coordination agreements	Government reports	Annual
Governance	Institutional Actors	Participating institutions	KPI95	No. institutions	Governance committee records	Annual

Governance	Companies	Participating companies	KPI96	No. companies	Chamber of commerce and mining associations	Annual
Governance	Non-Governmental Organizations (NGOs)	Participating NGOs	KPI97	No. NGOs	Governance committee records	Annual
Governance	Trade Associations	Participating trade associations	KPI98	No. associations	Governance committee records	Annual
Governance	Public–Private Partnerships (PPPs)	Active PPP projects	KPI99	No. projects	PPP agencies and development plans	Annual
Governance	Solidarity Sector	Cooperatives and associations involved	KPI100	No. cooperatives	Cooperative registries and chambers of commerce	Annual

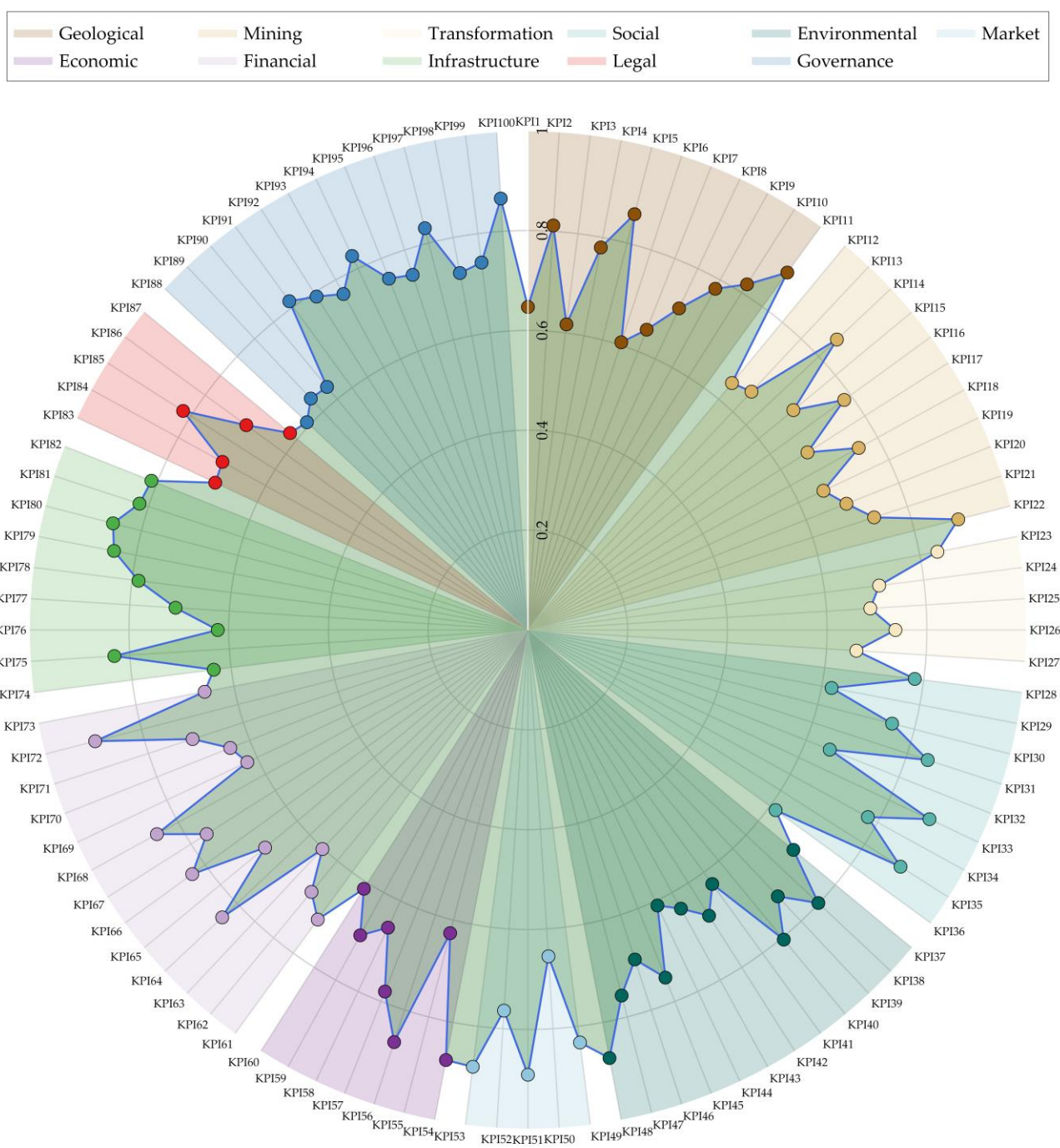


Figure 11. Multidimensional radar chart of illustrative KPIs. Developed by the authors using Python (Jupyter Notebook).

5. Discussion

5.1. Theoretical Implications

The proposed SMD framework contributes primarily at the conceptual rather than the methodological level. Existing sustainability studies have largely addressed mining through project-level assessments focused on environmental performance, ESG reporting, governance, life-cycle analysis, or corporate sustainability. In contrast, this study conceptualizes SMDs themselves as the units of strategic territorial planning by integrating eleven complementary dimensions that encompass geological, mining, transformation, environmental, social, market, economic, financial, infrastructure, legal, and governance components.

Rather than introducing a new sustainability assessment methodology, the framework synthesizes bibliometric, institutional, process-tracing, and geospatial evidence into a coherent conceptual architecture that provides an organizing structure for territorial mining planning. In doing so, it bridges disciplinary perspectives that have traditionally evolved separately within mining, sustainability, and territorial governance research.

An important theoretical implication is the shift from viewing MDs as predominantly geological or administrative entities to understanding them as complex socio-ecological systems whose long-term performance depends on interactions among natural resources, institutions, infrastructure, governance, markets, environmental constraints, and social dynamics. This systems perspective extends previous conceptualizations of MDs by explicitly incorporating territorial planning as an essential component of sustainability.

Because the proposed framework represents a conceptual architecture rather than an operational assessment model, its theoretical assumptions should be examined through future empirical applications in real MDs. Such validation will be essential to assess the practical relevance of the proposed planning dimensions, the applicability of the illustrative KPIs, and the robustness of the framework under different territorial contexts.

5.2. Policy Implications

In Colombia, the institutional analysis indicates that the recent regulatory reforms introduced through Law 2294 of 2023 and its subsequent regulatory instruments represent an important transition from conventional mining regulation toward a territorial governance approach. Rather than focusing exclusively on mineral extraction, the emerging policy framework incorporates objectives related to mining formalization, productive diversification, environmental rehabilitation, and regional development. Process tracing further illustrates that these reforms have evolved through successive institutional decisions involving national government agencies, planning authorities, and mining organizations, highlighting the importance of coordination among multiple actors during policy implementation.

From a planning perspective, the framework may assist public institutions by providing a structured methodology for identifying priority mining territories, organizing multidisciplinary information, and monitoring district performance through standardized indicators. Although the KPI system remains illustrative, it establishes a foundation for future evidence-based evaluation once official monitoring datasets become available. The framework should therefore be interpreted as a planning support instrument rather than a regulatory or decision-making model.

5.3. Comparison with Existing Frameworks

As shown in Table 1, the proposed SMD framework differs from existing international sustainability frameworks primarily in its planning perspective. Whereas current frameworks focus on improving sustainability reporting, operational performance,

certification, or governance at the company, project, operation, or national levels, the framework introduces the MDs as the fundamental territorial planning unit. This shift expands the scope of sustainability assessment from individual mining activities to the coordinated management of complex mining territories.

Rather than replacing existing sustainability frameworks, the proposed model complements them by providing an integrated territorial perspective that explicitly incorporates geological continuity, mineral potential, environmental constraints, infrastructure, institutional capacity, socioeconomic development, and governance within a single conceptual structure. This multidimensional integration enables strategic planning that extends beyond project boundaries and recognizes MDs as socio-ecological systems whose long-term sustainability depends on the interaction among natural resources, institutions, infrastructure, environmental conditions, and stakeholders.

From this perspective, existing frameworks may be viewed as complementary instruments operating at different decision-making scales. While standards such as GRI 14, ICMM, TSM, IRMA, and EITI guide improving corporate sustainability, reporting, certification, and transparency, the proposed SMD framework provides the territorial planning context within which these instruments can be strategically integrated. Consequently, rather than replacing existing sustainability assessment approaches, the proposed framework extends them by introducing MDs as the fundamental territorial planning unit for strategic and integrated sustainability planning. Nevertheless, because the framework remains conceptual, its practical applicability should be confirmed through future empirical applications in real MDs. Such validation will determine whether the proposed planning dimensions and illustrative KPIs can effectively support territorial planning and decision-making under different geological, institutional, and socioeconomic contexts.

6. Limitations

This study presents several limitations that should be considered when interpreting the proposed SMD framework. The principal limitation of this study is inherent to its conceptual nature. The framework was intentionally designed to establish the first multidimensional conceptualization of SMDs rather than to develop or validate an operational assessment methodology. Conceptual studies represent an initial stage of theory development, particularly in emerging research fields where empirical reference cases remain limited. At its current stage, the framework should therefore be interpreted as a conceptual planning model whose practical implementation and quantitative performance remain to be validated through empirical applications in real MD case studies.

Another limitation is that the framework has not yet been evaluated through structured expert consultation involving government agencies, mining companies, environmental authorities, local communities, indigenous organizations, and academic specialists. Such participatory validation could contribute not only to refining the proposed planning dimensions but also to assessing the relevance, feasibility, availability, and prioritization of the proposed KPIs under real planning conditions. Multi-stakeholder validation would further strengthen the legitimacy and practical applicability of the framework for territorial governance.

The institutional analysis focused on Colombia because it is among the first countries in which SMDPDs have recently entered the national regulatory agenda through Law 2294 of 2023. Nevertheless, institutional arrangements, governance structures, and planning traditions differ substantially across jurisdictions. Consequently, future comparative studies should examine the framework's adaptability across different legal and institutional contexts. Furthermore, MDs differ substantially across mineral commodities,

geological settings, production scales, environmental sensitivities, and institutional maturities, all of which may require context-specific adaptations of the framework.

Likewise, some indicators proposed in the illustrative KPI catalog may not yet be supported by publicly available or standardized datasets, particularly for governance, social, market, and territorial dimensions. Consequently, future research should identify measurable proxies, establish data-collection protocols, define weighting procedures, and evaluate the temporal stability of each indicator before operational implementation.

The bibliometric analysis was restricted to publications indexed in ScienceDirect, Scopus, and Web of Science. Although these databases provide broad international coverage, relevant evidence contained in regional journals, government reports, technical documents, and the grey literature may not have been captured. Likewise, bibliometric results depend on author-defined keywords and database indexing practices despite the normalization procedures adopted.

Future research should focus on transforming the proposed conceptual framework into an operational planning instrument through quantitative validation. A first step would involve pilot applications in emerging SMDs using official geological, mining, environmental, infrastructure, socioeconomic, governance, and production datasets to calibrate the proposed KPIs. In the Colombian context, the recently established Bajo Cauca District represents a particularly valuable opportunity because its institutional implementation is currently underway. Beyond KPI calibration, quantitative validation could incorporate multi-criteria decision analysis (MCDA) techniques, such as the Analytic Hierarchy Process (AHP), Best–Worst Method (BWM), or other weighting approaches, to prioritize planning dimensions, assign indicator weights, and construct composite sustainability indices at the district scale. Sensitivity and uncertainty analyses could subsequently evaluate the robustness of the framework under alternative weighting scenarios. At the same time, comparative applications across different MDs, mineral commodities, governance systems, and territorial contexts would provide evidence regarding its transferability and practical usefulness for strategic planning.

Despite these limitations, this study establishes the first integrated conceptual framework specifically designed for SMDs. By defining MDs as the fundamental territorial planning unit and integrating eleven complementary planning dimensions within a single conceptual architecture, the framework provides a robust conceptual foundation upon which future empirical validation, stakeholder evaluation, indicator calibration, and quantitative decision-support tools can be progressively developed.

7. Conclusions

This study presents the first integrated conceptual framework for SMDs, proposing that districts should be understood as multidimensional territorial systems rather than solely as geological entities, production areas, or administrative units. By integrating bibliometric evidence, institutional analysis, process tracing, and geospatial assessment, the study establishes a conceptual foundation for incorporating geological, mining, transformation, environmental, social, economic, financial, market, infrastructure, legal, and governance dimensions into strategic territorial planning.

The main theoretical contribution of this study is the conceptualization of SMDs as integrated territorial planning units that connect eleven complementary planning dimensions within a single framework. Unlike existing sustainability approaches, which predominantly assess individual mining projects or corporate performance, the proposed framework shifts the analytical focus toward the district as the fundamental territorial unit, providing a conceptual architecture that integrates geological potential, institutional governance, environmental constraints, infrastructure, and socioeconomic development. The bibliometric, institutional, and geospatial analyses collectively demonstrate that MDs

are increasingly evolving toward multidimensional territorial systems that require integrated planning approaches.

The principal practical contribution of the proposed framework is to organize the key planning dimensions, operational elements, and illustrative KPIs into a coherent planning-support structure. Rather than prescribing a decision-making methodology, the framework provides a systematic basis for multidisciplinary territorial assessments, strategic planning, and the development of monitoring systems that integrate heterogeneous information throughout the district life cycle.

The policy implications of this research are particularly relevant to countries that promote territorial mining governance. The Colombian case illustrates an emerging transition from conventional mining regulation to district-scale planning, in which mineral development is integrated with environmental management, productive diversification, infrastructure, and stakeholder coordination. Although developed from the Colombian experience, the conceptual architecture may also provide useful guidance for other mineral-producing regions seeking to strengthen sustainable territorial governance.

Future research should focus on empirically validating the proposed framework through pilot applications in SMDs, calibrating the proposed KPIs using official monitoring datasets, evaluating their feasibility through expert consultation involving government agencies, mining companies, environmental authorities, academia, and local communities, and assessing their applicability across different mineral commodities, governance contexts, and territorial scales. These efforts will provide the empirical evidence required to progressively transform the present conceptual framework into a robust territorial planning and decision-support instrument.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/resources15080103/s1>. GIS shapefiles: Geospatial layers used for the territorial analysis and map preparation. Python scripts: Scripts developed for bibliometric processing, data analysis, visualization, and framework construction. VOSviewer files: VOSviewer project files, including the consolidated RIS bibliographic database and bibliometric network files used for the literature analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

MDs	Mining districts
SMDs	Sustainable Mining Districts
SMDPDs	Special Mining Districts for Productive Diversification
SDGs	Sustainable Development Goals
ACI	Actor-Centered Institutionalism
KPIs	Key performance indicators
ESG	Environmental, Social, and Governance
SLO	Social License to Operate
SWOT	Strengths, Weaknesses, Opportunities, and Threats
NPV	Net Present Value
ICMM	International Council on Mining and Metals
TSM	Towards Sustainable Mining
FRM	Framework for Responsible Mining
SUSOP®	SUSustainable Operations
LPSPDP	Leading Practices for Sustainable Development Program
MPF	Mining Policy Framework
IRMA	Initiative for Responsible Mining Assurance
EITI	Extractive Industries Transparency Initiative
GRI	Global Reporting Initiative
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
ANM	National Mining Agency
SGC	Colombian Geological Survey
UPME	Mining and Energy Planning Unit
DNP	National Planning Department

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