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Selection and Operationalization of Sustainability Indicators for Mining Municipalities in the Amazon

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A B S T R A C T

Assessing sustainability in mining municipalities in the Amazon remains challenging due to limitations related to the availability, standardization, and operationalization of indicators at the territorial scale. In this study, we aimed to select and operationalize sustainability indicators applicable to mining municipalities in the Amazon. A systematic literature review was conducted using the Scopus database and complemented with institutional databases and publicly available datasets. A total of 148 indicators distributed across the environmental, economic, social, governance, and cultural dimensions were initially identified and evaluated using an eligibility matrix based on regional relevance, data availability, comparability, periodicity, methodological clarity, and reproducibility. The selection process resulted in a final set of 47 indicators suitable for comparative analyses at the municipal scale. The highest retention rates were observed in the governance (47.1%) and economic (45.0%) dimensions, reflecting the wider availability of standardized administrative data. In contrast, the environmental dimension showed the lowest retention rate because most indicators relied on modeling approaches or indirect remote sensing data. No indicators were retained in the cultural dimension due to the limited availability of standardized information and the predominance of qualitative attributes associated with the socio-territorial diversity of the Amazon. The final set comprises mainly indicators derived from administrative databases, geospatial information, and environmental monitoring systems with predominantly annual updates. The proposed framework provides an operational basis for comparative sustainability assessments and supports territorial management in mining municipalities across the Amazon.

Keywords: Territorial assessment, Amazon mining, Environmental governance, Territorial planning, Municipal indicators.

Seleção e operacionalização de indicadores de sustentabilidade para municípios mineradores da Amazônia

R E S U M O (PT-BR)

A avaliação da sustentabilidade em municípios mineradores da Amazônia enfrenta limitações relacionadas à disponibilidade, padronização e operacionalização de indicadores em escala territorial. O estudo teve como objetivo selecionar e operacionalizar indicadores de sustentabilidade aplicáveis a municípios mineradores amazônicos. A pesquisa foi desenvolvida por meio de revisão sistemática da literatura indexada na base Scopus, complementada por consulta a bases institucionais e dados públicos. Inicialmente, foram identificados 148 indicadores distribuídos nas dimensões ambiental, econômica, social, governança e cultural, posteriormente submetidos a uma matriz de elegibilidade composta por critérios de relevância regional, disponibilidade, comparabilidade, periodicidade, clareza metodológica e reprodutibilidade. O processo resultou na seleção de 47 indicadores compatíveis com análises comparativas em escala municipal. As maiores taxas de retenção ocorreram nas dimensões de governança (47,1%) e econômica (45,0%), associadas à ampla disponibilidade de bases administrativas padronizadas, enquanto a dimensão ambiental apresentou menor retenção devido à predominância de métricas dependentes de modelagem e sensoriamento indireto. A dimensão cultural não apresentou indicadores elegíveis em razão da baixa disponibilidade de dados padronizados e da predominância de atributos qualitativos associados à diversidade socioterritorial amazônica. Predominaram indicadores derivados de bases administrativas, dados geoespaciais e sistemas de monitoramento ambiental, com periodicidade majoritariamente anual. O conjunto final fornece uma base operacional para avaliações comparativas da sustentabilidade e para o desenvolvimento de ferramentas metodológicas aplicadas à gestão territorial em municípios mineradores da Amazônia.

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Palavras-Chaves: Avaliação territorial, Mineração amazônica, Governança ambiental, Planejamento territorial, Indicadores municipais.

Selección y operacionalización de indicadores de sostenibilidad para municipios mineros de la Amazonia

R E S U M E N (SPANISH)

La evaluación de la sostenibilidad en municipios mineros de la Amazonia enfrenta limitaciones relacionadas con la disponibilidad, estandarización y operacionalización de indicadores a escala territorial. Este estudio tuvo como objetivo seleccionar y operacionalizar indicadores de sostenibilidad aplicables a municipios mineros amazónicos. Se realizó una revisión sistemática de la literatura utilizando la base de datos Scopus, complementada con bases de datos institucionales y fuentes de información pública. Inicialmente, se identificaron 148 indicadores distribuidos en las dimensiones ambiental, económica, social, de gobernanza y cultural, los cuales fueron evaluados mediante una matriz de elegibilidad basada en criterios de relevancia regional, disponibilidad de datos, comparabilidad, periodicidad, claridad metodológica y reproducibilidad. El proceso de selección dio lugar a un conjunto final de 47 indicadores adecuados para análisis comparativos a escala municipal. Las mayores tasas de retención se observaron en las dimensiones de gobernanza (47,1%) y económica (45,0%), debido a la mayor disponibilidad de datos administrativos estandarizados. En contraste, la dimensión ambiental presentó la menor tasa de retención, ya que gran parte de los indicadores dependía de modelos o de datos obtenidos mediante sensores remotos indirectos. No se retuvieron indicadores en la dimensión cultural debido a la limitada disponibilidad de información estandarizada y al predominio de atributos cualitativos asociados con la diversidad socioterritorial de la Amazonia. El conjunto final está compuesto principalmente por indicadores derivados de bases de datos administrativas, información geoespacial y sistemas de monitoreo ambiental con actualización predominantemente anual. El marco propuesto proporciona una base operativa para evaluaciones comparativas de la sostenibilidad y contribuye al desarrollo de herramientas metodológicas orientadas a la gestión territorial en municipios mineros de la Amazonia.

Palabras clave: Evaluación territorial, Minería amazónica, Gobernanza ambiental, Planificación territorial, Indicadores municipales.

1. Introduction

Mining activities significantly influence the territorial organization of regions where the exploitation of natural resources constitutes a major economic base. In the Amazon, this influence occurs within a context characterized by high environmental sensitivity, socio-territorial diversity, and institutional heterogeneity, factors that shape how the effects of mining are manifested across the territory. Empirical evidence indicates that the expansion of mining activities in the region is associated with deforestation, land use change, and increasing pressure on protected areas and traditional territories (Sonter et al., 2017; Mataveli et al., 2022; Rudke et al., 2020).

The relationship between mining and sustainability cannot be inferred from isolated economic indicators. Studies show that mining activities may coexist with environmental degradation, social inequalities, and limitations in local institutional capacity, particularly in regions dependent on extractive economies (Agusdinata et al., 2022; Antwi et al., 2017; Mancini and Sala, 2018). This pattern is particularly relevant in Amazonian contexts, where territorial dynamics involve interactions among natural systems, limited infrastructure, and multiple forms of land use.

Assessing these dynamics requires sustainability indicators that can represent different dimensions of the socio-environmental system in a measurable manner. Indicators are used to translate complex phenomena into observable variables, enabling comparative analyses and temporal monitoring (Meadows, 1998; Moldan, Janoušková & Hák, 2012; Singh et al., 2012). The literature indicates, however, that the usefulness of these instruments depends on their operationalization based on available, comparable, and methodologically consistent data (OECD, 2008; Ibañez Iralde et al., 2024; Guarini et al., 2025).

Despite advances in the development of indicator systems, limitations remain in their application at the territorial scale. Studies indicate that broad indicator sets often include conceptually relevant variables that cannot be operationalized at the municipal scale due to the lack of standardized data, scale

incompatibilities, or dependence on complex modeling approaches (Ibañez Iralde et al., 2024; Feil et al., 2025; Valizadeh and Hayati, 2025). This limitation is more evident in regions such as the Amazon, where data availability is uneven and territorial heterogeneity imposes additional constraints on territorial comparability.

In the case of mining municipalities, the application of sustainability indicators at the territorial scale faces limitations associated with data availability, scale compatibility, and methodological standardization. Studies on the development and selection of indicators indicate that variables frequently proposed in the literature cannot be operationalized at the municipal scale, either because consistent databases are unavailable or because they rely on indirect modeling approaches or information that is not comparable across territorial units (OECD, 2008; Singh et al., 2012; Feil et al., 2025). These limitations constrain the use of indicators in comparative analyses and reduce their applicability in public management contexts.

Against this background, we aim to select and operationalize sustainability indicators applicable to Amazonian mining municipalities by identifying them in the literature, verifying them in secondary databases, and applying eligibility criteria.

2. Material and Methods

2.1 Research design

This study adopted a bibliographic and documentary research design focused on the systematization of sustainability indicators. This article corresponds to the second stage of a broader methodological framework, in which the previous stage defined the analytical dimensions of sustainability in mining contexts (Pinheiro and Braga, 2026). The present stage aimed to select and operationalize sustainability indicators based on these dimensions through a targeted literature search, verification using secondary databases, and the application of eligibility criteria. The set of indicators structured at this stage provides the basis for future applications in sustainability assessments at the municipal scale.

The combination of literature review, documentary screening, and verification using secondary databases followed procedures described in the indicator development literature, which recommend the initial identification of a broad set of variables followed by a refinement process based on explicit selection criteria (Ayadi et al., 2024; Feil et al., 2025; Valizadeh and Hayati, 2025). This procedure made it possible to clearly define the selection stages and reduce inconsistencies in the composition of the final indicator set.

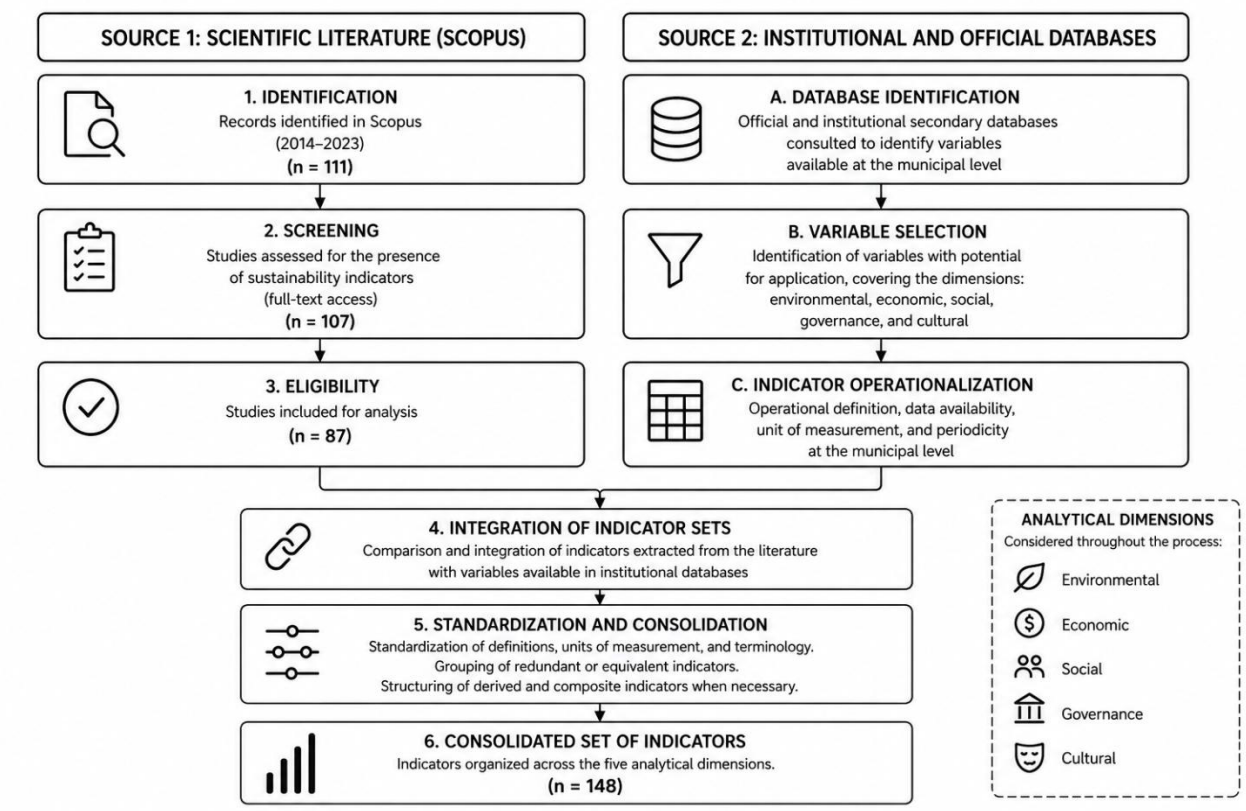
The unit of analysis consisted of Amazonian mining municipalities. The choice of this scale was driven by the availability of standardized secondary databases, the possibility of comparisons across territorial units, and its applicability to public management analyses, including the assessment of socio-environmental and institutional conditions associated with mining activities.

2.2 Preliminary identification and organization of indicators

The preliminary identification of indicators was based on the analytical dimensions of sustainability defined by Pinheiro and Braga (2026), which provided the conceptual framework for this stage. Based on these dimensions, a targeted search was performed in the Scopus database using the following search strategy: ("sustainability indicator" OR "indicator framework" OR "sustainability assessment") AND (mining OR extractive) AND (region* OR territorial OR governance OR development), considering the period from 2014 to 2023 and restricting the search to scientific articles. Exploratory searches using a similar strategy were also conducted in other databases. However, no studies meeting the adopted search criteria were retrieved. Therefore, Scopus was used as the primary database because it provided the studies eligible for indicator extraction.

The search strategy resulted in 111 articles, of which 107 were analyzed in full. Four studies were not available in full text at the time of data collection and were therefore excluded from the analysis. Among the studies analyzed, 20 did not present sustainability-related indicators or variables and were excluded. In total, 87 studies were considered eligible for indicator extraction. The process of study identification, screening, indicator extraction, and verification using secondary databases to consolidate the final indicator set is presented in Figure 1.

Figure 1 - Flow of identification, screening, extraction, and consolidation of sustainability indicators from scientific literature and institutional databases (2014–2023).
Figura 1 – Fluxo de identificação, triagem, extração e consolidação de indicadores de sustentabilidade a partir da literatura científica e de bases institucionais (2014–2023).



Note: (n) refers to the number of studies or indicators, depending on the stage.
Note 2: Figure 1 was prepared by the authors with the assistance of a generative artificial intelligence tool for the organization of its graphical elements and was subsequently reviewed and edited.
Source: Authors (2026).
Fonte: Autores (2026).

Indicators, metrics, or variables related to sustainability assessment were extracted based on the full-text analysis of the eligible studies, considering different scales of analysis. Inclusion was conditioned on the existence of an operational definition, a measurement unit, and the potential for adaptation to the municipal scale (OECD, 2008; Ibañez Iralde et al., 2024).

Information regarding the source study, authorship, year of publication, indicator name, definition, associated analytical dimension, indicator type, measurement unit, scale of application, and potential data source was recorded in structured spreadsheets for each identified indicator. This procedure ensured the

traceability of indicators to their original studies. Indicators were preliminarily assigned to the analytical dimensions according to their predominant function.

As illustrated in Figure 1, the verification stage using secondary databases was conducted in parallel with the extraction of indicators from the literature to identify variables available for application at the municipal scale. Official and institutional databases covering the environmental, economic, social, governance, and cultural dimensions were considered, as presented in Table 1. The indicators identified in the literature were cross-checked against the variables available in these databases to assess their empirical feasibility.

Table 1 - Databases and institutional sources consulted for verification and preliminary operationalization of the indicators.
Tabela 1 - Bases de dados e fontes institucionais consultadas para verificação e operacionalização preliminar dos indicadores.

Analytical dimension	Databases and institutional sources	Main application
Environmental	ANA, SNIRH, SNIS, MapBiomas, PRODES, TerraBrasilis, MMA, IBAMA, ICMBio, SEEG	Water resources, sanitation, land cover and land use, deforestation, emissions, and environmental conservation
Economic	ANM, RAIS, CEMPRE, National Treasury, state SEFAZ agencies, IBGE	Mineral production, formal employment, public revenue, economic dynamics, and productive dependence
Social	IBGE, UNDP, SIM, e-Gestor AB, CadÚnico	Demography, income, health, social vulnerability, and access to services
Governance	Transparency Portal, SICAR, official municipal government websites (transparency and local legislation), municipal legislation	Transparency, regularization, planning, management instruments, and institutional control
Cultural	Traditional Territories Platform and official municipal websites	Identification of traditional communities and aspects of cultural heritage

Note: ANA = National Water and Basic Sanitation Agency. SNIRH = National Water Resources Information System. SNIS = National Sanitation Information System. PRODES = Amazon Deforestation Monitoring Program. MMA = Ministry of the Environment and Climate Change. IBAMA = Brazilian Institute of Environment and Renewable Natural Resources. ICMBio = Chico Mendes Institute for Biodiversity Conservation. SEEG = Greenhouse Gas Emissions and Removals Estimation System. ANM = National Mining Agency. RAIS = Annual Social Information Report. CEMPRE = Brazilian Business Commitment for Recycling. UNDP = United Nations Development Programme. SIM = Mortality Information System.
Source: Authors (2026).
Fonte: Autores (2026).

The initial set of indicators exhibited redundancies, terminological variations, and conceptual overlap. A standardization and consolidation stage was therefore conducted based on conceptual equivalence, operational definitions, and measurement units, grouping indicators that represented the same phenomenon while maintaining the traceability of the original sources (Ibañez Iralde et al., 2024; Guarini et al., 2025).

Following the consolidation process, a total of 148 indicators were identified and organized into the five analytical dimensions adopted in this study (Appendix). During this process, the indicators were classified according to their operational nature to align the measurement approach with the type of data available and their analytical function. Three categories were adopted: primary indicators, corresponding to variables directly observable in statistical or institutional databases; binary indicators, representing the presence or absence of institutional conditions or instruments; and composite indicators, resulting from the aggregation of two or more elementary variables (OECD, 2008; Ayadi et al., 2024; Guarini et al., 2025).

2.3 Eligibility matrix

The indicators were selected using an eligibility matrix designed to evaluate each variable against explicit retention criteria. The use of formal criteria in indicator selection has been described in the literature as a means of ensuring consistency and reproducibility (Singh et al., 2012; Moldan, Janoušková and Hák, 2012).

The definition of the criteria simultaneously considered the conceptual relevance and empirical feasibility of the indicators, following approaches applied to sustainability assessment in productive systems and territorial contexts (Eslami et al., 2023; Jiskani et al., 2021). Six criteria were adopted: regional relevance, availability, comparability, periodicity, methodological clarity, and reproducibility, as presented in Table 2.

Table 2 - Eligibility criteria for the selection of sustainability indicators.
Tabela 2 - Critérios de elegibilidade para seleção dos indicadores de sustentabilidade.

Criterion	Operational definition
Regional relevance	Capacity of the indicator to represent recurring dynamics in Amazonian mining municipalities
Availability	Existence of accessible data in an official or institutional source
Comparability	Possibility of standardized comparison among municipalities
Periodicity	Existence of an identifiable update frequency
Methodological clarity	Presence of an explicit definition, formula, or criterion
Reproducibility	Possibility of applying the indicator to other municipalities or time series

Source: Authors (2026).
Fonte: Autores (2026).

Suitability to the municipal scale, the existence of an identifiable database, and the consistency of measurement units were considered when evaluating indicators, as these factors are necessary to ensure comparability among municipalities (OECD, 2008; Jiskani et al., 2021; Eslami et al., 2023).

Indicators exhibiting conceptual overlap were assessed according to methodological clarity and data availability, and those with greater potential for practical application were retained. Indicators lacking an operational definition or an identifiable data source were excluded. Indicators with partial data limitations were retained when they exhibited analytical relevance and potential applicability to some municipalities, considering the recurrent limitations associated with dimensions such as governance and culture (Antwi et al., 2017; Agusdinata et al., 2022).

The application of the eligibility matrix consisted of the systematic evaluation of each indicator against the established criteria. Inclusion in the final set required simultaneous compliance with the minimum criteria defined. This procedure determined the final set of selected indicators, whose composition and distribution across analytical dimensions are presented in the Results section.

3. Results and Discussion

Applying the eligibility matrix reduced the initial set of 148 indicators to 47, corresponding to a retention rate of 31.8%. Reductions of this magnitude are common in indicator selection processes, in which the simultaneous application of criteria related to data availability, territorial comparability, and operationalization at the local scale substantially restricts the initial set of variables (Singh et al., 2012; Valizadeh and Hayati, 2025). Studies on indicator harmonization have shown that preliminary sets frequently include conceptually relevant metrics that lack empirical feasibility for application in comparative territorial analyses, particularly at the municipal scale (Ibañez Iralde et al., 2024; Guarini et al., 2025).

In mining contexts, additional limitations arise from the predominance of indicators originally developed for productive, corporate, or sectoral scales, whose adaptation to territorial sustainability

assessments presents methodological constraints and limitations in data availability (Fonseca, McCall and Duarte, 2019; Agusdinata et al., 2022). Studies on mining sustainability indicate that metrics that rely on indirect modeling, non-standardized data, or the absence of consistent time series tend to exhibit limited applicability in subnational analyses (Eslami et al., 2023; Feil et al., 2025). The distribution of the selected indicators across analytical dimensions, together with their respective retention rates relative to the initial set, is presented in Table 3.

Table 3 - Distribution of the selected indicators by dimension and their respective retention rates.
Tabela 3 - Distribuição dos indicadores selecionados por dimensão e respectivas taxas de retenção.

Dimension	Initial	Selected	Retention (%)
Environmental	65	15	23,1
Economic	20	9	45,0
Social	40	15	37,5
Governance	17	8	47.1
Cultural	6	0	0.0
Total	**148**	**47**	**31.8**

Source: Authors (2026).
Fonte: Autores (2026).

Retention rates varied across the analytical dimensions, with lower values observed for the environmental dimension (23.1%) and higher values for the economic (45.0%) and governance (47.1%) dimensions. The lower retention observed for the environmental dimension was associated with the predominance, within the initial set, of indicators that relied on modeling approaches, indirect sensing techniques, or biophysical scales that were incompatible with the availability of municipal data. Studies on sustainability assessment indicate that environmental metrics often present greater operational complexity and lower territorial standardization than socioeconomic and administrative indicators (Moldan, Janoušková & Hák, 2012; Singh et al., 2012).

The higher retention rates in the economic and governance dimensions were associated with the greater availability of administrative data systematically produced by public institutions, a condition that favors territorial comparability, temporal continuity, and methodological reproducibility at the municipal scale (OECD, 2008; Feil et al., 2025). The social dimension showed an intermediate retention rate (37.5%), associated with the coexistence of widely standardized indicators and metrics dependent on irregular surveys or spatial scales that are not compatible with municipal analyses, a recurring limitation in territorial sustainability indicator systems (Singh et al., 2012; Ibañez Iralde et al., 2024; Valizadeh and Hayati, 2025).

The absence of indicators in the cultural dimension was associated with the limited availability of standardized and comparable data at the municipal scale, as well as with the predominance of qualitative and context-specific attributes, which limit their operationalization in quantitative territorial analyses (Ibañez Iralde et al., 2024; Guarini et al., 2025). This result also reflects the high socio-territorial variability observed in Amazonian mining municipalities, where cultural aspects are often associated with the presence of Indigenous peoples, traditional communities, and specific forms of social organization that are heterogeneously distributed across the territory (Agusdinata et al., 2022; Athayde et al., 2017). Studies conducted in the Amazon indicate that mining-related transformations may affect territorial dynamics, livelihoods, and local sociocultural relationships, aspects that are frequently examined through qualitative approaches and for which standardized metrics at the municipal scale remain scarce (Palacios et al., 2021; Sonter et al., 2017). This pattern highlights the limitations of quantitatively operationalizing the cultural dimension and reinforces the need to develop indicators compatible with the socio-territorial diversity of the Amazon.

The final set consisted predominantly of primary and composite indicators derived from secondary databases, with limited participation of binary indicators. Administrative, geospatial, and environmental monitoring data predominated, with mostly annual update frequencies and a high degree of observability. This pattern is consistent with methodological recommendations that prioritize indicators that are directly measurable, comparable, and amenable to periodic updates in territorial sustainability assessments (Meadows, 1998; OECD, 2008; Guarini et al., 2025).

3.1 Environmental dimension

The selected environmental indicators were organized into three major axes: resource use, territorial transformation, and environmental quality. Metrics derived from geospatial, administrative, and environmental monitoring data predominated, exhibiting high observability and recurrent application in territorial sustainability assessments (Li et al., 2017; Kucukvar et al., 2014; Yang et al., 2018; Silva et al., 2023). The indicator set consisted mainly of variables related to land cover and land use, environmental quality, water resources, solid waste, and emissions, reflecting a prioritization of indicators compatible with continuous monitoring and comparability at the municipal scale (Charikinya et al., 2017; Eslami et al., 2023).

In Amazonian mining municipalities, the retention of these indicators was associated with their ability to represent territorial changes frequently linked to the expansion of mining activities. Studies have shown that mining in the region is associated with changes in land use, the expansion of degraded areas, and increasing pressure on forest ecosystems, aspects directly related to the indicators selected for the final set (Sonter et al., 2017; Mataveli et al., 2022; Rudke et al., 2020). The predominance of metrics derived from remote sensing and environmental monitoring also reflects the greater availability of standardized data for biophysical variables at the municipal scale, a recurrent condition in territorial environmental assessment systems (Charikinya et al., 2017; Eslami et al., 2023).

The selected indicators included metrics for both environmental pressures and system states, encompassing the change in land use, emissions, solid waste, and water quality. This set broadened the capacity to represent the different forms of environmental degradation associated with mining activities and supported integrated analyses at the territorial scale (Antwi et al., 2017; Devkota et al., 2021; Konare et al., 2023; Palacios et al., 2021). The inclusion of physicochemical water parameters complemented the indicator set by incorporating variables sensitive to local changes in water bodies, which are frequently used in environmental monitoring programs and assessments of anthropogenic impacts (Chidiac et al., 2023; Zainurin et al., 2022). Table 4 presents the selected environmental indicators, including their operational definitions, indicator types, data sources, and update frequency.

Table 4 - Selected environmental indicators, including operational definitions, types, data sources, and periodicity at the municipal scale.

Tabela 4 - Indicadores ambientais selecionados, com definição operacional, tipo, fonte de dados e periodicidade em escala municipal.

Indicator	Operational description	Type	Data source	Periodicity	Unit
Per capita water consumption	Total water consumption in the municipality divided by the resident population	Primary	Administrative data	Annual	m^3/inhabitant/year
Per capita solid waste generation	Total amount of solid waste generated in the municipality adjusted by population	Primary	Administrative data	Annual	kg/inhabitant/year
Reclaimed area	Total area reclaimed after mining activities within the municipal territory	Primary	Geospatial data	Irregular	ha

Degraded area	Total area degraded by anthropogenic activities within the municipal territory	Primary	Geospatial data	Annual	ha
Waste recycling rate	Proportion of solid waste recycled relative to the total generated in the municipality	Primary	Administrative data	Irregular	%
Per capita GHG emissions	Total greenhouse gas emissions in the municipality adjusted by population	Primary	Modeled data (SEEG)	Annual	tCO_2e/inhabitant/year
Waste collection coverage	Proportion of the population served by solid waste collection services	Primary	Administrative data	Annual	%
Protected area	Proportion of the municipal territory under legal protection	Primary	Geospatial data	Annual	%
Forest cover	Proportion of the municipal territory covered by forest vegetation	Primary	Geospatial data	Annual	%
Deforestation rate	Annual deforested area within the municipal territory	Primary	Geospatial data	Annual	km^2/year
Hotspots	Annual number of hotspots recorded within the municipal territory	Primary	Geospatial data	Annual	no./year
Water electrical conductivity	Mean electrical conductivity measured in monitored water bodies within the municipality	Primary	Monitoring data	Annual	µS/cm
Water pH	Mean hydrogen potential of water in monitored water bodies within the municipality	Primary	Monitoring data	Annual	–
Dissolved oxygen	Mean dissolved oxygen concentration in monitored water bodies within the municipality	Primary	Monitoring data	Annual	mg/L
Water turbidity	Mean turbidity measured in monitored water bodies within the municipality	Primary	Monitoring data	Annual	NTU

Source: Authors (2026).
Fonte: Autores (2026).

The final composition highlights the predominance of observable indicators derived from administrative, geospatial, and environmental monitoring data, a characteristic that enhances territorial comparability, reproducibility, and applicability at the municipal scale (Charikinya et al., 2017; Eslami et al., 2023; OECD, 2008). The selection prioritized variables supported by available historical series, regular updates, and well-established methodological approaches, criteria that are frequently adopted in the operationalization of sustainability indicators (Guarini et al., 2025). Taken together, these indicators capture different dimensions of the environmental changes associated with mining and constitute a set of metrics applicable to comparative analyses across Amazonian municipalities (Sonter et al., 2017; Pinheiro et al., 2026).

3.2 Economic dimension

The selected economic indicators were organized into three major axes: productive structure, public finances, and mining dependence. Metrics derived from administrative and fiscal databases predominated, with annual coverage and a high degree of institutional standardization, conditions that favor territorial comparability and their application in municipal sustainability assessments (Rodrigues et al., 2021; Chen et al., 2021). The indicator set incorporates variables associated with wealth generation, productive structure, public revenue, and labor dynamics, which are frequently used in territorial assessments of the economic dependence on extractive activities (Li et al., 2017; Yang and Guo, 2021; Shang et al., 2019; Oppon et al., 2023).

In Amazonian mining municipalities, the retention of these indicators was associated with their ability to represent patterns of productive specialization and economic dependence linked to the exploitation of natural resources. Studies have shown that mining activities tend to promote localized economic growth, often accompanied by sectoral concentration and limited productive diversification (Antwi et al., 2017; Devkota et al., 2021). Empirical evidence indicates that municipalities with a strong mining presence exhibit a high share of the extractive sector in the local economy and greater exposure to fluctuations in commodity markets, which is directly related to the inclusion of indicators of economic dependence and productive diversification in the final indicator set (Mentis and Moonsammy, 2022; Singh et al., 2012; Guarini et al., 2025). Table 5 presents the selected economic indicators, including their operational definitions, indicator types, data sources, and update frequency.

Table 5 – Selected economic indicators, including operational definitions, types, data sources, and periodicity at the municipal scale.
Tabela 5 – Indicadores econômicos selecionados, com definição operacional, tipo, fonte de dados e periodicidade em escala municipal.

Indicator	Operational description	Type	Data source	Periodicity	Unit
GDP per capita	Municipal Gross Domestic Product divided by the resident population	Primary	Administrative data	Annual	BRL/capita
Mining dependence in GDP	Share of mining activities in the municipal Gross Domestic Product	Primary	Administrative data	Annual	%
Public revenue per capita	Total municipal revenue divided by the resident population	Primary	Administrative data	Annual	BRL/capita
Formal employment by economic sector	Share of formal employment relationships by sector in total formal employment	Primary	Administrative data	Annual	%
Per capita energy consumption	Total electricity consumption divided by the resident population	Primary	Administrative data	Annual	kWh/capita
CFEM revenue	Total revenue from the Financial Compensation for Mineral Exploration (CFEM) collected by the municipality	Primary	Administrative data	Annual	BRL
Infrastructure investment	Municipal public expenditure on infrastructure	Primary	Administrative data	Annual	BRL
Proportion of local public procurement	Share of local suppliers in municipal public expenditures	Primary	Administrative data	Irregular	%
GDP diversification	Share of non-mining sectors in the municipal Gross Domestic Product	Primary	Administrative data	Annual	%

Source: Authors (2026).
Fonte: Autores (2026).

Indicators such as the share of mining in GDP, CFEM revenue, and productive diversification help represent the degree of economic specialization and the influence of mining activities on the municipal economic structure (Shang et al., 2019; Mentis & Moonsammy, 2022; Mota et al., 2017). In Amazonian contexts, these patterns are often associated with limited economic diversification and greater vulnerability to external fluctuations related to mineral commodity markets (Roy et al., 2023; Cordella et al., 2023).

The indicator set also incorporates variables related to municipal fiscal capacity, income circulation, and the intensity of economic activity, including metrics of public revenue, intergovernmental transfers, energy consumption, and local public procurement. The inclusion of these variables reflects the relevance of fiscal structure and the capacity to internalize the economic effects of mining in territories dependent on extractive activities (Moldan, Janoušková & Hák, 2012; Singh et al., 2012; Meadows, 1998; OECD, 2008). Per capita energy consumption is frequently used as an indirect indicator of the intensity of economic activity, whereas the proportion of local public procurement indirectly represents the capacity of local suppliers to participate in municipal public expenditures and their potential contribution to the circulation of financial resources within the territory (Ibañez Iralde et al., 2024; Park and Kremer, 2017; Maldonado et al., 2019; Eslami et al., 2023).

The final composition highlights the predominance of indicators derived from administrative and fiscal databases, which favors the availability of time series, methodological standardization, and territorial comparability at the municipal scale (OECD, 2008; Guarini et al., 2025). These characteristics enhance the reproducibility of the indicator set and support its application in comparative analyses of economic sustainability across Amazonian mining municipalities.

3.3 Social dimension

The selected social indicators were organized into three groups: socioeconomic conditions, access to basic services, and demographic characteristics of the territory. Metrics derived from administrative databases predominated, with mostly annual updates and a high degree of institutional standardization, a condition that favors territorial comparability and application at the municipal scale (Li et al., 2017; Yang and Guo, 2021). The indicator set incorporates classical variables related to well-being, inequality, and access to public services, which are frequently used in territorial assessments of social conditions and the distribution of opportunities (Falck & Spangenberg, 2014; Olalekan et al., 2023; Rivera et al., 2014).

In Amazonian mining municipalities, the retention of these indicators was associated with their ability to represent asymmetries between economic growth and social conditions. Studies have shown that the expansion of mining activities may increase income and formal employment without proportionally translating these gains into improvements in living conditions, resulting in the persistence of social inequalities and vulnerabilities (Antwi et al., 2017; Devkota et al., 2021; Mancini and Sala, 2018). Evidence from the Amazon region indicates that mining-related growth often occurs in a spatially concentrated manner, with an unequal distribution of economic benefits and limited improvements in social indicators (Agusdinata et al., 2022; Mota et al., 2017). Table 6 presents the selected social indicators, including their operational definitions, indicator types, data sources, and update frequency.

Table 6 – Selected social indicators, including operational definitions, types, data sources, and periodicity at the municipal scale.

Tabela 6 – Indicadores sociais selecionados, com definição operacional, tipo, fonte de dados e periodicidade em escala municipal.

Indicator	Operational description	Type	Data source	Periodicity	Unit
Population density	Resident population divided by municipal area	Primary	Administrative data	Annual	inhabitants/km²
Poverty rate	Proportion of the population	Primary	Administrative	Annual	%

	living in poverty		data		
Unemployment rate	Proportion of the economically active population unemployed	Primary	Administrative data	Annual	%
Access to drinking water	Proportion of the population with access to drinking water	Primary	Administrative data	Annual	%
Child labor	Proportion of children engaged in child labor	Primary	Administrative data	Irregular	%
Formal employment rate	Share of workers with formal employment contracts	Primary	Administrative data	Annual	%
Infant mortality	Number of infant deaths per thousand live births	Primary	Administrative data	Annual	‰
Primary health care coverage	Proportion of the population covered by primary health care	Primary	Administrative data	Annual	%
School enrollment rate (6–14 years)	Proportion of children enrolled in school	Primary	Administrative data	Annual	%
Extreme poverty rate	Proportion of the population living in extreme poverty	Primary	Administrative data	Annual	%
Homicide rate	Number of homicides per 100,000 inhabitants	Primary	Administrative data	Annual	cases/100 thousand
Adequate housing	Proportion of households with adequate housing conditions	Primary	Administrative data	Annual	%
Per capita income	Average income per inhabitant	Primary	Administrative data	Annual	BRL/capita
Access to sanitation services	Proportion of the population with access to sanitation services	Primary	Administrative data	Annual	%
Rural population	Proportion of the population residing in rural areas	Primary	Administrative data	Decennial	%

Source: Authors (2026).
Fonte: Autores (2026).

The selected set enables representation of different dimensions of social conditions in Amazonian mining municipalities, including access to public services, living conditions, and social vulnerability. Studies indicate that variables related to sanitation, health, education, and labor markets are widely used to assess social inequalities and the provision of essential services at the territorial scale (Antwi et al., 2017; Palacios et al., 2021; Chen et al., 2021; Prasad et al., 2022). In Amazonian municipalities, the availability of these services exhibits strong spatial heterogeneity, often linked to population dispersion, infrastructure limitations, and institutional constraints (Guimarães et al., 2020).

The inclusion of variables related to poverty, violence, child labor, and the spatial distribution of the population expands the capacity of the indicator set to represent processes of social exclusion and territorial inequality in contexts characterized by limited territorial integration and restricted access to public policies (Agusdinata et al., 2022; Konare et al., 2023; Rodrigues et al., 2021). The predominance of indicators derived from national administrative databases supports methodological standardization, the availability of time series, and territorial comparability in municipal social sustainability assessments (Eslami et al., 2023; Charikinya et al., 2017).

3.4 Governance dimension

The selected governance indicators were organized into three axes: institutional capacity, public management, and fiscal structure. Metrics based on administrative data predominated, with an emphasis on observable and standardized indicators, which favors territorial comparability and application at the municipal scale. The exclusion of indicators associated with corporate practices and organizational metrics reflects limitations in the compatibility between instruments designed for the corporate level and territorial analyses applied to subnational units (Charikinya et al., 2017; Eslami et al., 2023; Falck & Spangenberg, 2014).

In Amazonian mining municipalities, the retention of these indicators was associated with their ability to represent the institutional role of public authorities in mediating the territorial effects of mining activities. Studies have shown that municipal administrative capacity directly influences the conversion of mining revenues into infrastructure, public services, and environmental control mechanisms (Agusdinata et al., 2022; Mota et al., 2017). Evidence on territorial governance in Amazonian mining municipalities indicates that differences in administrative capacity, institutional structure, and public planning directly affect the implementation of territorial management instruments and municipal policies, particularly in contexts characterized by mining dependence and territorial inequalities (Enríquez, Formigosa and Câmara, 2025; Gumiero, 2023). Table 7 presents the selected governance indicators, including their operational definitions, indicator types, data sources, and update frequency.

Table 7 – Selected governance indicators, including operational definitions, types, data sources, and periodicity at the municipal scale.
Tabela 7 – Indicadores de governança selecionados, com definição operacional, tipo, fonte de dados e periodicidade em escala municipal.

Indicator	Operational description	Type	Data source	Periodicity	Unit
Public transparency	Municipal public management transparency index	Composite	Administrative data	Annual	index
Existence of a master plan	Existence of an active municipal master plan	Binary	Administrative data	Irregular	yes/no
Existence of an environmental council	Existence of an active municipal environmental council	Binary	Administrative data	Irregular	yes/no
Environmental and S&T expenditure per capita	Municipal expenditure on environmental management, science, and technology, divided by the resident population	Primary	Administrative data	Annual	BRL/capita
CAR coverage	Proportion of the area registered in the Rural Environmental Registry relative to the total area eligible for registration within the municipality	Primary	Administrative data	Annual	%
Dependence on intergovernmental transfers	Share of intergovernmental transfers in total municipal revenue	Primary	Administrative data	Annual	%
CFEM share in revenue	Proportion of municipal revenue derived from CFEM	Primary	Administrative data	Annual	%
Expenditure on risk and disaster management per capita	Municipal expenditure on risk and disaster management divided by the resident population	Primary	Administrative data	Irregular	BRL/capita

Source: Authors (2026).

Fonte: Autores (2026).

The selected set highlights the central role of municipal institutional capacity in mediating the territorial effects of mining in Amazonian municipalities. The predominant retention of indicators related to public management, territorial planning, and fiscal structure reflects the greater availability of standardized administrative data for assessing governmental performance at the municipal scale. In mining contexts, differences in the administrative and financial capacities of municipalities directly influence the implementation of public policies, territorial planning, and the management of socio-environmental pressures associated with mining activities (Enríquez, Formigosa and Câmara, 2025; Gumiero, 2023).

The final composition also highlights limitations in the operationalization of qualitative dimensions of governance, particularly those related to institutional effectiveness and social participation, for which comparable data at the municipal scale remain scarce. Therefore, observable indicators derived from national administrative databases predominate. This favors territorial comparability, the availability of time series, and methodological reproducibility in municipal governance assessments (Eslami et al., 2023; Charikinya et al., 2017).

4. Conclusion

The present study resulted in the selection and operationalization of 47 sustainability indicators applicable to Amazonian mining municipalities, organized into the environmental, economic, social, and governance dimensions. The application of the eligibility criteria revealed a predominance of observable indicators derived mainly from administrative databases, geospatial data, and institutional monitoring systems, with predominantly annual update frequencies and operational compatibility with the municipal scale. This pattern reflects the prioritization of metrics that support territorial comparability, periodic updates, and methodological reproducibility, aspects considered central to territorial sustainability assessment systems.

The results indicate that indicator retention varied across the analytical dimensions according to the availability, standardization, and compatibility of information with municipal analyses. Economic and governance indicators exhibited the highest retention rates due to the broad availability of structured administrative data, whereas the environmental dimension showed a greater exclusion of metrics that rely on modeling approaches, indirect sensing techniques, or biophysical scales incompatible with municipal databases. The absence of cultural indicators highlights persistent limitations in the quantitative operationalization of sociocultural attributes within comparative indicator systems, particularly in Amazonian contexts characterized by high socio-territorial diversity and the presence of Indigenous peoples and traditional communities.

The final configuration of the indicator set demonstrates that the application of sustainability indicators in mining municipalities depends not only on conceptual relevance but also on the availability of databases compatible with standardized territorial analyses. In this regard, the study helps reduce the gap between theoretical indicator frameworks and their empirical feasibility at the municipal scale by providing an operational set of indicators applicable to comparative sustainability assessments in Amazonian mining contexts.

The results also highlight limitations in the availability and standardization of territorial information, particularly for dimensions associated with cultural aspects, social participation, and institutional effectiveness. These limitations indicate the need to develop operational metrics capable of incorporating greater socio-territorial diversity into quantitative sustainability assessments. Future studies may advance the empirical application of the selected indicator set and the development of composite indicators and

aggregation methods capable of supporting integrated sustainability assessments in Amazonian mining municipalities.

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