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REVIEW ARTICLE

Key geographical indicators for environmental, social and economic sustainability of land use

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ABSTRACT

Sustainable land-use planning requires spatially explicit indicators capable of integrating environmental, social, and economic dimensions of territorial systems. Geo-indicators have been widely applied to assess land-use dynamics, environmental pressures, urban expansion, and spatial inequalities. Paradoxically, an integrated, the methodological and conceptual framework remains largely fragmented across the literature. The study objectives were to strengthen the conceptual and methodological basis for integrating geo-indicators into evidence-based land-use planning frameworks. To ensure methodological rigor, this study employed a systematic review and bibliometric analysis conforming to the preferred reporting items for systematic reviews and meta-analyses guidelines. Scientific records were retrieved from Scopus and Web of Science for the period 1998–2025. From an initial set of 497 records, 41 case-based studies were selected after duplicate removal, screening, and eligibility assessment. Bibliometric analysis was conducted utilizing RStudio (an integrated development environment for R programming), a bibliometric package (an R package designed for bibliometric analysis) and visualization of similarities viewer software. This analysis aimed to assess trends in scientific production, thematic structures, keyword co-occurrence, and international collaboration networks. The results indicate a significant increase in scientific production after 2018, reaching a peak in 2025, reflecting the growing relevance of geo-indicators in sustainability science. The thematic landscape resolved into three distinct clusters: environmental impacts and sustainability transitions, spatial modeling using geographic information systems coupled with multi-criteria decision analysis, and urban and territorial planning applications. Geographic information systems integrated with analytical hierarchy process, fuzzy logic, spatial modelling, and scenario simulation were identified as the most frequently applied methodological approaches. Environmental geo-indicators were found to dominate the literature, while social and economic dimensions remain underdeveloped and inconsistently integrated across studies. Such an asymmetry underscores a persistent disconnect in translating multidimensional sustainability frameworks into operational tools for territorial analysis. The main limitation identified is the absence of a standardized geo-indicator framework capable of integrating environmental, social, and economic dimensions across spatial and temporal scales. These findings demonstrate that while geo-indicators constitute powerful tools for land-use sustainability assessment, their ultimate utility depends on standardized methodologies, geospatial systems interoperability, and the incorporation of socioeconomic dimensions.

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INTRODUCTION

Sustainability in territorial planning involves the balanced management of natural resources to ensure environmental integrity, social equity, and economic development without compromising future generations (Elorrieta Sanz *et al.,* 2016; Smith *et al.,* 2023). In territorial planning, sustainability aims to balance socio-economic development with ecological constraints while ensuring responsible land and resource management (Global Forest Resources Assessment, 2020). Territorial planning policies should integrate environmental, social, and economic dimensions to balance development and conservation while maintaining life-support systems (UN-Habitat, 2020). In contemporary territorial planning, sustainability indicators serve as critical diagnostic tools to quantify and monitor progress toward sustainable development objectives (Tran *et al.,* 2024). Geo-indicators are spatially explicit measures that integrate environmental, social, and economic variables within geographic information systems (GIS) to support territorial analysis and decision-making. In contrast to conventional sustainability indicators, geo-indicators integrate explicit spatial dimensions and multidimensional sustainability criteria, allowing for a more granular evaluation of land-use dynamics. At the global scale, established frameworks such as the United Nations (UN) sustainable development goals (SDGs), the Driving Forces–Pressures–State–Impact–Response (DPSIR) framework, the Millennium Ecosystem Assessment (MA), and the System of Environmental-Economic Accounting (SEEA) enable integrated assessment of environmental, social, and economic territorial dimensions (Guo *et al.,* 2024; Mkhitaryan *et al.,* 2026). Rising pressure on natural systems—driven by the degradation of approximately 60 percent (%) of resources and a projected global population of 9.7 billion by 2050—emphasizes the need for robust, time-comparable spatial metrics to support territorial planning (United Nations, 2019). Consequently, sustainability indicators have emerged as institutionalized mechanisms to evaluate human-induced pressures on socio-ecological systems, thereby informing policy frameworks that foster equitable and resilient territorial development (Yang *et al.,* 2018). The transformation of sustainability indicators into geo-indicators incorporates the spatial dimension into sustainability assessment, allowing analysis of socio-economic and land-use dynamics linked to land use land cover (LULC). Unlike conventional indicators, this framework effectively delineates territorial gradients, critical vulnerabilities, and intricate spatial dynamics (Chaudhari *et al.,* 2024; Gioia *et al.,* 2024; Mathenge *et al.,* 2022). Advances in geotechnologies have enabled the integration and analysis of environmental, socioeconomic, and biophysical data, enhancing understanding of human–environment interactions across spatial scales (Académico *et al.,* 2025; Angelita, 2020). Since the 1980s, thematic mapping and geographic information systems (GIS) have supported environmental impact assessment, including LULC change, environmental degradation, urban expansion, and resource pressure (Handmer, 1980; Tsatsaris *et al.,* 2021). By endorsing geospatial methodologies and indicators for sustainable territorial and spatial planning, the 1992 Rio de Janeiro Earth Summit lent crucial institutional support to this approach (McCammon, 1992; Scott and Rajabifard, 2017). In the 21st century, the growing need to monitor climate change, assess progress on the SDGs, and anticipate future scenarios has solidified geo-indicators as tools for dynamically integrating the environmental, social, and economic dimensions of territories in a time-comparable manner (Márquez Delgado *et al.,* 2021; ONU, 2012). Cloud computing (e.g., Google Earth Engine (GEE)) and geospatial big data analysis have improved the processing of large territorial datasets, enabling real-time monitoring of land cover, vegetation productivity, water availability, and climate risks, and strengthening

geo-indicators in territorial planning (Gorelick *et al.,* 2017). Consequently, the integration of geo-indicators into territorial planning and management enhances decision-making frameworks by delivering spatially explicit evaluations, longitudinal assessments, and strategic guidance for sustainable development policies (Zhang *et al.,* 2024). The integration of spatial analysis and territorial modelling has enhanced sustainability assessment from a forward-looking, evidence-based perspective. Geostatistical techniques and spatial modelling enable geo-indicators to construct land-use change scenarios and anticipate the effects of planning decisions and policies (Bielecka, 2020; Smelror, 2020). Furthermore, integrating time-series analysis with dynamic modeling facilitates the evaluation of spatiotemporal variations in territorial systems, thereby enhancing the precision of multiscale assessments regarding anthropogenic impacts on ecosystems (Pricope *et al.,* 2019). These tools facilitate the identification of high-risk areas and change thresholds, supporting the implementation of territorial management strategies and the design of corrective measures at local and regional levels (Rezvani *et al.,* 2023). Systematic literature reviews in this field have been crucial in consolidating the available knowledge on geo-indicators applied to territorial planning (Argandoña-Castro and Peña-Cortés, 2025). While global efforts have extensively classified sustainability metrics—ranging from systematic dimensional analyses (Grassi et al., 2026; Parra-Pulido *et al.,* 2024) to screening frameworks designed to select representative indicator subsets (Behjat *et al.,* 2024); significant challenges remain. Chief among these are the persistent shortage of cohesive, integrative frameworks and the difficulty of adapting global metrics to localized contexts (Donatti *et al.,* 2020). Consequently, systematic reviews facilitate a rigorous synthesis of existing literature, establishing a robust foundation to guide future research while illuminating current knowledge gaps and methodological limitations (El Archi *et al.,* 2023). Some studies have applied geo-indicators to assess the impact of urban and rural dynamics on sustainability. In the Jakarta–Bandung Mega Urban Region (JBMUR), Indonesia, a local sustainability index (LSI) revealed spatial interdependence among local units, with many subdistricts showing low economic and social sustainability but moderate environmental performance (Pravitasari *et al.,* 2022). In Cuenca, Ecuador, a GIS-based approach was deployed to examine the relationship between urban fabric typologies and sustainability indicators, yielding critical insights for urban planning frameworks (Calderón *et al.,* 2024). Similarly, studies conducted in the Yangtze River Delta Basin in China and in Tanta, Egypt, highlight the roles of landscape characteristics and land use in rural and urban sustainability, using GIS and analytical hierarchical processes (AHP). These studies facilitated the identification of priority zones for urban densification and the preservation of agricultural land (Abdrabo *et al.,* 2021; Meng *et al.,* 2024). In Germany, spatial trade-offs in wind energy allocation are emphasized through participatory and transparent approaches balancing costs, ecological impacts, and interregional equity (Lehmann *et al.,* 2021). These empirical cases illustrate the capacity of geo-indicators to enhance assessment precision and optimize territorial management strategies. While the application of geo-indicators has expanded significantly, a standardized, multi-dimensional framework that seamlessly synthesizes environmental, social, and economic parameters remains absent. Existing studies remain fragmented, with a predominant focus on environmental indicators and limited methodological guidance for multidimensional integration across spatial scales. Geo-indicators contribute to sustainable land-use planning by enabling spatially explicit, multi-scale analysis of environmental and socio-economic processes, supporting evidence-based territorial management and decision-making. However, the

full utility of these metrics remains restricted by methodological discrepancies and an asymmetrical integration of sustainability dimensions. This review addresses these limitations by systematically synthesizing 41 Scopus- and Web of Science-indexed studies and combining bibliometric analysis with a systematic review approach. By analyzing methodological trends, spatial techniques, and dimensional integration patterns, this study introduces a structured framework designed to optimize geo-indicator operationalization in sustainable land-use planning. In this context, the study addresses two research questions: (i) what types of geo-indicators are used to assess land-use sustainability across environmental, social, and economic dimensions, and (ii) which spatial analysis methodologies are most frequently applied for their integration in sustainable territorial management. By systematically synthesizing spatial metrics and sustainability frameworks within territorial planning, this review offers a refined conceptual architecture for geo-indicators. Unlike previous reviews focused mainly on environmental indicators or regional applications, this study examines the integration of environmental, social, and economic dimensions using geospatial analytical approaches. Using bibliometric analysis and a systematic review, this study identifies methodological trends and emerging research areas, and highlights gaps in geo-indicator frameworks for sustainable territorial management. A systematic evaluation of literature indexed in Scopus and Web of Science (WoS) was conducted to characterize the geo-indicators and geospatial methodologies used in multi-dimensional land-use sustainability assessments. Based on this analysis, the study proposes a framework that integrates the main dimensions of sustainability with spatial analysis based on geo-indicators. This systematic review investigates the application of geo-indicators in evaluating land-use sustainability and highlights the spatial techniques that are most commonly employed to facilitate sustainable territorial management. The aims of this review study are to strengthen the conceptual and methodological basis for integrating geo-indicators into evidence-based land-use planning frameworks. This study has been carried out in ESPOL Polytechnic University, Guayaquil, Ecuador in 2026.

METHODOLOGY

The main purpose of the methodological base is to evaluate geo-indicators and demonstrate their strategic role in analyzing, monitoring and evaluating the sustainability of territories. This enables the spatial and temporal representation of changes induced by human activities on natural and socio-economic systems (Fig. 1). To address the stated objective, a comprehensive framework was established to synthesize the interactions among territorial systems, spatial indicators, and their corresponding geospatial evaluation tools. Fig. 2 illustrates this conceptual model, which informs the analytical structure of the study and demonstrates how geo-indicators can be incorporated into sustainable territorial planning processes. These conceptual frameworks (Figs. 1 and 2) were derived from the systematic synthesis of the reviewed literature and reflect the most frequently identified methodological patterns in geo-indicator research. Their conceptual architecture is derived from synthesizing bibliometric insights with the outcomes of a systematic literature review. This process combined a systematic review with a bibliometric analysis. The methodological process followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, which are divided into four key phases (Fig. 3). The Identification phase prioritizes the retrieval of records from comprehensive academic databases to guarantee an extensive compilation of relevant studies. In the Screening phase, the records are examined by reviewing titles and abstracts to determine their relevance to the research topic. Subsequently, during the Eligibility phase, full

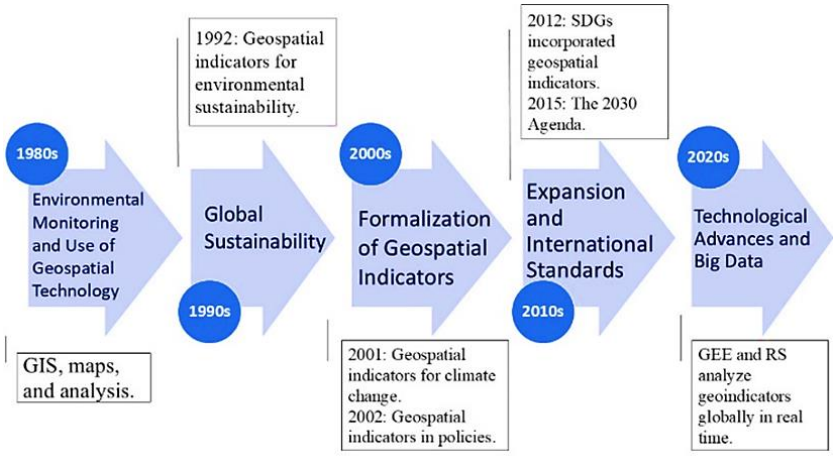

Fig. 1: Conceptual evolution of geo-indicators and their integration into spatial sustainability assessment frameworks

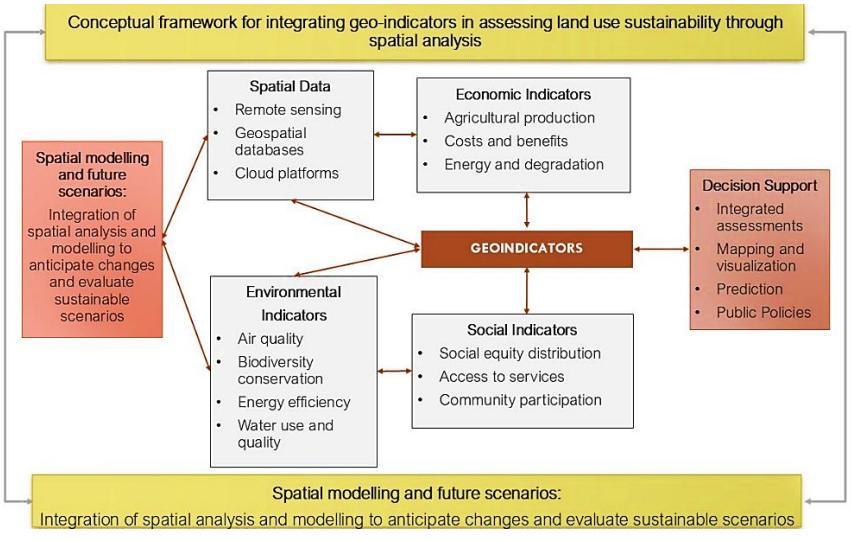

Fig. 2: Conceptual framework for the integration of geo-indicators in land use sustainability assessment through spatial analysis

articles are reviewed to assess their suitability against the established criteria. Ultimately, the inclusion phase guarantees that only studies satisfying the predefined eligibility criteria proceed to the final analysis, thereby facilitating a rigorous and consistent evaluation of the selected literature.

Identification

The search strategy was conducted using two major academic databases, Scopus and Web of Science (WoS). These databases were selected due to their broad multidisciplinary coverage, rigorous peer-review indexing standards, and extensive use in systematic reviews within environmental and spatial sciences. Deploying these methods in tandem guarantees methodological rigor, enhances data quality, and ensures the reproducibility of results—a dual approach heavily endorsed within bibliometric and systematic review literature (Pranckutė, 2021). This search focused on geo-indicators applied to the assessment of environmental, social, and economic sustainability, with the aim of identifying their applications in land use and land cover (LULC).

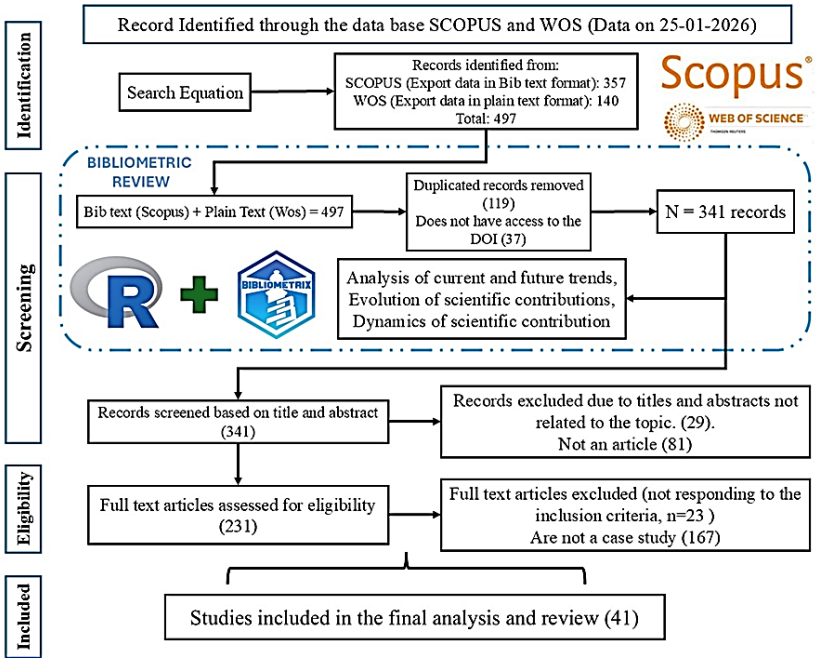

Fig. 3: Flowchart of the PRISMA-based methodology used for systematic review and bibliometric analysis

The search equations were structured using the keywords “sustainability indicators” and “spatial analysis,” along with their respective synonyms. To maximize the precision and relevance of the retrieved literature, Boolean logic was applied throughout the search strategy. Specifically, the Boolean operator OR was used to connect synonyms within each category, whereas the Boolean operator AND was used to intersect different search clusters (Table 1). The bibliographic search covered the period from 1998 to 2025, identifying early conceptual developments in spatial sustainability indicators and their methodological evolution, ensuring representation of both foundational and recent contributions. While omitting supplementary databases (e.g., Google Scholar, IEEE Xplore, and regional repositories) alongside grey literature may limit the review's overall comprehensiveness, this restriction was deliberately imposed to ensure methodological rigor, data quality, and study reproducibility. Additional keyword families were considered to enhance coverage, including geospatial indicators, land-use indicators, environmental indicators, spatial sustainability assessment, and territorial indicators. The literature search was executed across both databases on January 25, 2026, yielding a total of 497 articles (357 from Scopus and 140 from WoS). Subsequently, the retrieved records were exported in platform-compatible formats, utilizing BibTeX for Scopus and Plain Text for WoS (Yasin and Bacsi, 2025). Subsequently, these files were imported into RStudio, enabling efficient organisation and data cleaning for further bibliometric analysis (Yubo *et al.,* 2023). Data processing was carried out using a bibliometric approach that integrated RStudio, visualization of similarities viewer (VOSviewer), and Bibliometrix, enabling analysis of the dynamics of scientific production, the thematic structure of the literature, and emerging research trends in the field of geo-indicators. This procedure enabled the delineation of publication trends, thematic configurations, and epistemic networks, thereby offering a systematic view of the field's evolution and trajectory across diverse research domains over time (Kemeç *et al.,* 2023).

Table 1: Search strategy in Scopus and WoS for identifying articles related to spatial analysis and sustainability indicators

Search	Keywords and boolean operators
I. Spatial analysis	"GIS" OR "Spatial Analysis" OR "Geospatial Analysis" OR "Spatial Data Analysis" OR "Geographic Analysis" OR "Spatial Statistics" OR "Spatial Modeling" OR "Geographic Information Analysis" OR "Spatial Pattern Analysis" OR "Spatial Data Modeling" OR "Spatial Distribution Analysis" OR "Spatial Investigation" OR "Geostatistical Analysis" OR "Spatial Evaluation" OR "Spatial Examination" OR "Spatial Assessment" (The use of OR allows for including all possible synonyms for "Spatial Analysis")
II. Sustainability indicators	"sustainability indicators" OR "Sustainability metrics" OR "Sustainability measures" OR "Sustainability benchmarks" OR "Sustainability performance indicators" OR "Sustainability assessment criteria" OR "Sustainability evaluation indicators" OR "Sustainability indices" OR "Sustainability parameters" OR "Sustainability variables" OR "Sustainability criteria" OR "Sustainability standards" OR "Sustainability monitoring indicators" OR "Environmental performance indicators" OR "KPIs" OR " Key performance indicators " (The use of OR ensures the inclusion of various terms related to "Sustainability Indicators")
Final strategy	I and II (Combining both the spatial analysis and sustainability indicators searches for a comprehensive and precise search)

Screening

To ensure the relevance and methodological quality of the studies included in the review, inclusion and exclusion criteria were established (Costal *et al.,* 2021; Natvig *et al.,* 2025). The exclusion criteria comprised duplicate records, articles without digital object identifier (DOI) access, studies falling outside the designated timeframe, and non-peer-reviewed documents, such as technical reports or institutional publications. Additionally, works that did not address applied case studies or that did not meet the methodological requirements for territorial sustainability assessment were excluded. The initial screening process removed 119 duplicate records and 37 articles without a DOI, reducing the total to 341 articles. Subsequently, during the title and abstract screening phase, 29 articles were excluded due to a lack of direct relevance to geo-indicators in sustainability, while an additional 81 records were omitted because they did not constitute peer-reviewed academic research. Among the discarded articles were studies that, despite utilizing spatial analysis tools such as GIS, failed to explicitly address geo-indicators or their application in sustainability to territorial management. In general, these works focused on specific applications, such as optimizing logistics services or managing infrastructures through digital environments and three-dimensional visualization, without establishing clear links to sustainability assessment in its environmental, social, or economic dimensions (Alabbasi *et al.,* 2024; Labib and Watfa, 2023). Consequently, these studies were deemed to fall outside the thematic and methodological boundaries established for this review.

Eligibility

During the eligibility assessment phase, the remaining 231 articles were reviewed to ensure they met the previously established inclusion criteria. This stage entailed a critical evaluation of the full-text articles, prioritizing three analytical dimensions: the underlying methodology, the specific geo-indicators evaluated, and the geographical context of the studies. The methodology was assessed to ensure that the studies employed rigorous scientific approaches, while the geo-indicators were analyzed to ensure they were appropriate and aligned with the environmental, social, and economic dimensions of sustainability. To ensure practical relevance, the inclusion criteria mandated that the literature consist of applied research set within appropriate geographical contexts, spanning both urban and rural landscapes. The filtering process excluded 167 studies that did not use case studies, limiting their relevance to the practical approach of this review. This decision was made to ensure methodological comparability across empirical applications of geo-indicators in real-world land-use contexts. Furthermore, 23 articles were excluded on the basis that they failed to

adequately address the application of geo-indicators within a land-use sustainability framework. Finally, 41 articles were selected that met all the inclusion criteria. These studies were considered methodologically sound, as they provide relevant empirical evidence on the application of geo-indicators in sustainable territorial management. The exclusion process followed predefined PRISMA criteria to ensure methodological rigor, reproducibility, and relevance to the research objectives. To maintain a highly consistent and comparable dataset, strict exclusion criteria were applied; specifically, the review omitted theoretical papers without empirical applications, studies omitting GIS methodologies, and research failing to evaluate geo-indicators across environmental, social, or economic dimensions of sustainable land use.

Dataset design and methodological separation between bibliometric and systematic review analyses

The relationship between the datasets used in this study is clarified to ensure methodological transparency. A total of 497 records were initially retrieved from Scopus and Web of Science for bibliometric analysis. After data cleaning and preprocessing in RStudio, 421 publications were retained for bibliometric analysis to ensure data quality and consistency. From this same initial dataset, a PRISMA-based screening process was applied to identify relevant empirical studies, resulting in 41 articles selected for the systematic review. Consequently, the bibliometric analysis and systematic review serve as complementary yet distinct dimensions of this study: the bibliometric dataset elucidates macro-level publication trends and scientific mapping, while the systematic review dataset facilitates a granular, qualitative evaluation of geo-indicator applications in land-use sustainability.

Systematic review studies

Finally, 41 studies were included in the systematic review, selected after a rigorous evaluation to ensure they met all the established inclusion criteria. The included studies addressed the application of geo-indicators in assessing land-use sustainability across environmental, social, and economic dimensions. Furthermore, all selected articles utilized empirical case studies, thereby facilitating a comparative analysis of geo-indicator applications across diverse territorial contexts. This final sample provided a diverse and representative empirical basis, enabling a comprehensive analysis of the application of geo-indicators in sustainable territorial planning in a variety of contexts.

Analysis of the PRISMA systematic review

A methodological evaluation of the selected studies was conducted, considering the study design, the validity of the geo-indicators used, and the quality of the data employed. A qualitative quality assessment was applied to ensure methodological coherence, focusing on the robustness of study design, clarity in geo-indicator application, data quality, and relevance to land-use sustainability contexts. While a formal quantitative risk-of-bias scoring system was not deployed, study quality was rigorously appraised using uniform qualitative criteria to guarantee dataset reliability. This process helped identify potential selection and publication biases, while the information analysis was developed through a qualitative synthesis aimed at recognizing patterns in the use of geo-indicators to assess land-use sustainability across different territorial contexts. Additionally, several variables were analyzed to systematically characterize the reviewed studies. Specifically, the data extraction protocol captured the DOI to guarantee publication traceability, the country of origin to evaluate regional distribution, and the geographical scale of application—categorized into urban or rural environments. Furthermore, the studies were classified by the sustainability domains they addressed (environmental, social, and economic). On the methodological side, the spatial analysis methods and GIS tools used, such

as ArcGIS and QGIS, were examined to assess the precision of the construction of the geo-indicators. The degree of integration between GIS and sustainability indicators was analyzed, categorised into low, medium, or high levels, enabling evaluation of how spatial data is linked to sustainability metrics. By tracking these variables, this study establishes a rigorous literature profile that maps methodological configurations, regional approaches, and critical research gaps in the deployment of geo-indicators for sustainable territorial governance (Table 2). To address the predominantly descriptive nature of previous geo-indicator reviews, this study provides a structured quantitative synthesis of the literature. The bibliometric analysis quantifies scientific production trends over time, identifies thematic clusters based on keyword co-occurrence, and maps collaboration networks at the country level. In addition, geo-indicator applications were systematically classified according to sustainability dimensions (environmental, social, and economic), GIS methodologies, and spatial scales. Consequently, this integrated methodology transitions from a purely narrative synthesis to an objective, quantitative evaluation of geo-indicator research, enhancing the analytical rigor and reproducibility of the findings. Finally, the study selection process was represented using the PRISMA diagram, which transparently shows the different filtering stages and the 41 articles included in the review, ensuring the rigour, transparency, and reproducibility of the study.

Scientific contribution dynamics

Scientific production on geo-indicators applied to land-use sustainability shows a growth trend from 1998 to 2025, totalling 421 publications. As illustrated in Fig. 4, the temporal evolution of publication productivity follows an exponential trajectory (R^2 ~ 0.88). This strong coefficient of determination confirms the steady consolidation of the discipline and underscores its accelerating relevance within territorial sustainability and land-use planning across diverse contexts worldwide**.** The analysis identifies three evolutionary periods. The emergence period (1998–2008) is characterized by limited scientific production, averaging fewer than four articles per year and representing approximately 8% of total publications in isolated peaks. Although initially constrained in analytical scope, the early integration of GIS and multicriteria decision-making techniques in agricultural, forestry, and rural planning provided the foundational methodology for developing spatiotemporally comparable geo-indicators (Boers and Cottrell, 2007; Tiwari *et al*., 1999) (Graymore *et al.,* 2009; Sheppard, 2011). The consolidation period (2009–2017) shows sustained growth, with 8–18 publications per year (34% of total output), reflecting methodological and conceptual maturation. This stage is characterized by thematic diversification and the transition toward integrated approaches. In the environmental dimension, spatial modelling and territorial dynamics predominate, focusing on biomass estimation, bioenergy planning, and urban impact assessment (Sahoo *et al.,* 2016). In the social dimension, indicators of habitability and quality of life are incorporated into transport planning and residential design (Miller *et al.,* 2013). From an economic standpoint, these metrics serve to reconcile productive efficiency with territorial equity throughout both urban and rural frameworks (Xu and Coors, 2012). The expansion period (2018–2025) exhibits the highest scientific dynamism, with a marked increase since 2020 and a peak in 2025 (59 publications). This expansion is propelled by the global sustainability agenda, climate change imperatives, and territorial resilience demands, coupled with the burgeoning availability of multi-source geospatial datasets and advanced analytical technologies. Recent studies integrate environmental, social, and economic dimensions, extend temporal horizons, and develop geo-indicators for scenario analysis, water management, food security, urban sustainability, and climate risk assessment (Amini *et al.,* 2020; Duan *et al.,* 2021). This expansion is

Table 2: Analytical variables used for the systematic evaluation of geo-indicator studies

Variable	Operational description
DOI	Unique digital identifier of the analyzed article.
Country	Country or countries where the study was conducted.
Scale	Territorial level of the spatial analysis, such as local, municipal, regional, national, continental, or global.
Sustainability domain	Sustainability dimension addressed by the study: environmental, social, economic, or institutional.
Spatial analysis methods used	Spatial analysis methods applied in the study.
Sustainability indicator	Indicator, index, or metric used to assess sustainability.
GIS tools	GIS software, platform, or geospatial environment used.
GIS Integration–Indicators	Degree of integration between GIS and sustainability indicators: low, medium, or high.
Type of spatial data	Type of spatial data used, such as vector, raster, remote sensing (RS), census, administrative, or field data.
Temporal approach	Way in which the study incorporates the temporal dimension, such as cross-sectional, longitudinal, multitemporal, or time-series analysis.

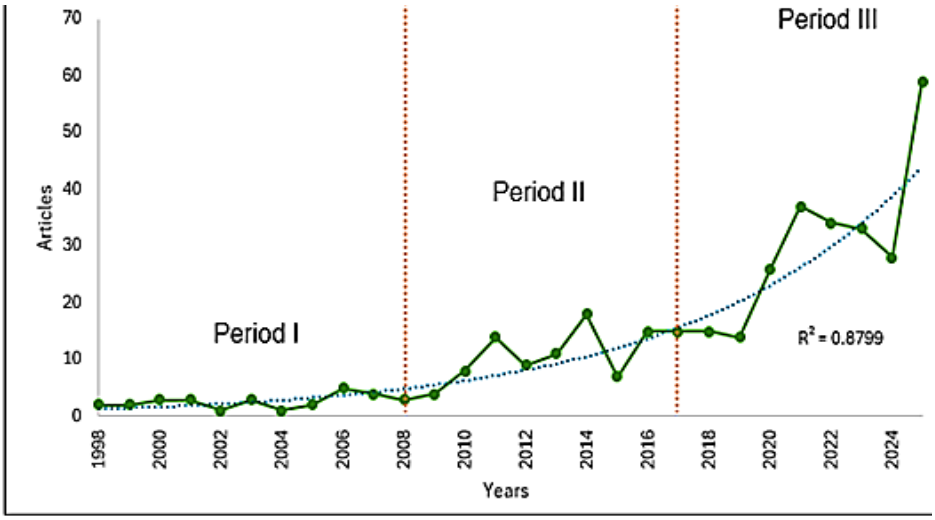

Fig. 4: Temporal dynamics of scientific production in studies of indicators for territorial management sustainability (1998 - 2025)

also supported by advances in geospatial computing, which have evolved significantly since the 1992 Rio Earth Summit and the subsequent adoption of the UN SDGs. Recent advancements in computational capacity for handling high-volume geospatial and socio-economic data have paved the way for more dynamic, multi-dimensional territorial assessments.

International scientific collaboration

The global scientific collaboration network (Fig. 5) shows that China (11.03%), the USA (10.06%), and Italy (7.63%) are the main centres of scientific production in land-use sustainability research. These countries serve as central nodes, underscoring their strategic importance in global knowledge production and international collaboration. Spain shows notable output but mainly regional collaboration within Europe. Australia and England function as bridges between Asia and North America, facilitating methodological and conceptual transfer in territorial monitoring. Egypt, Iran, and Canada show lower production but maintain collaboration mainly with the USA, indicating a dependent cooperation pattern. Overall, the research

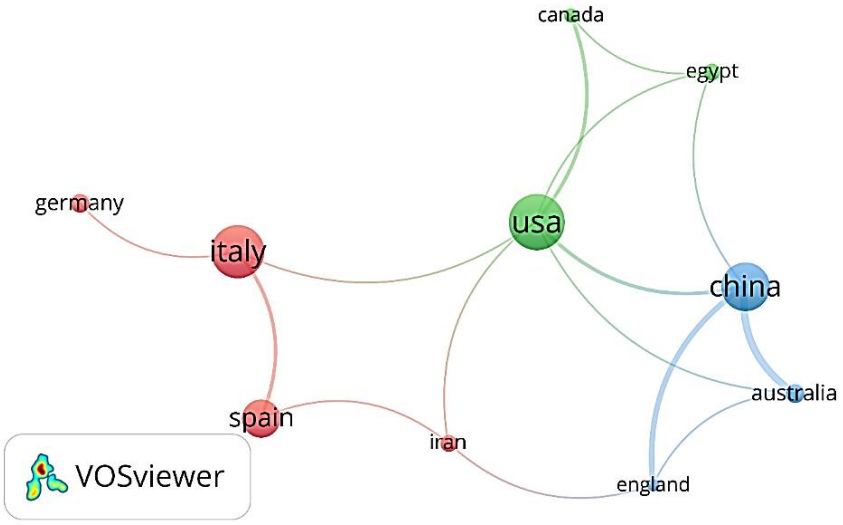

Fig. 5: Global scientific collaboration network in land use indicators and sustainability studies

network exhibits a pronounced dominance by the Global North, whereas developing nations remain significantly underrepresented within the literature on geo-indicator and territorial sustainability research.

Thematic structure and current orientation: current trends

The keyword co-occurrence analysis identifies three thematic clusters structuring scientific production on the environmental, social, and economic sustainability of land use. As illustrated in Fig. 6, the keyword co-occurrence network delineates the primary thematic trajectories and research trends dominating sustainable territorial management literature. The red cluster, associated with environmental impacts and sustainability, reflects a strong focus on the environmental dimensions of land use and energy transition. Keywords such as sustainability, biodiversity, landscape, challenges, and impacts highlight tensions between energy development and ecosystem conservation. Bioenergy has emerged as a prominent sector within renewable energy research, triggering critical debates regarding biodiversity depletion, landscape alteration, and multifaceted sustainability trade-offs. These findings emphasise the link between sustainable territorial management and the environmental and social impacts of energy systems. Characterized by its focus on methodologies and decision-support systems, the green cluster underscores the pivotal role of GIS in embedding spatial data within planning frameworks. The co-occurrence of model, optimisation, management, AHP, and renewable energy indicates a shift towards multicriteria and optimisation approaches in resource and energy management. GIS is no longer limited to cartographic representation but functions as an analytical tool for scenario evaluation and prioritisation of territorial alternatives. This underscores the imperative for robust geo-indicators to operationalize sustainability within public policy frameworks and localized initiatives. The blue cluster, linked to urban planning and sustainable development, includes terms such as urban planning, land use, and city, highlighting the practical application of sustainability in territorial planning. It reflects growing interest in how urbanisation, expansion, and land-use change affect territorial balance. The trend highlights the necessity of incorporating environmental, social, and economic indicators into urban planning to

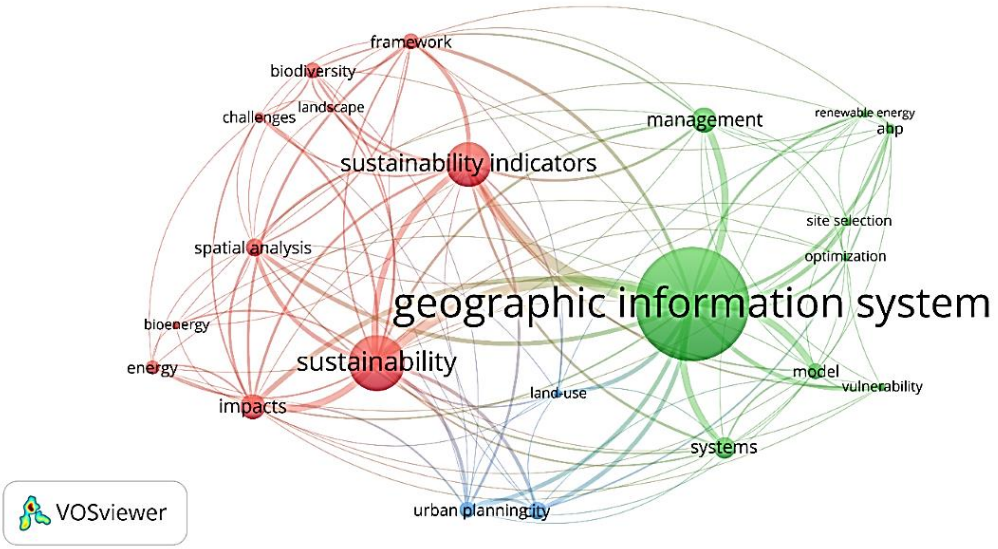

Fig. 6: Keyword co-occurrence map in the literature on sustainability and territorial management

foster more resilient cities, signifying a shift from theoretical development to practical application in territorial management through integrated, data-driven, and participatory approaches**.**

Conceptual evolution and emerging lines

The bibliometric thematic map reveals the conceptual structure of the research field on indicators and land use sustainability (Fig. 7). In the motor themes quadrant, renewable energy and land use planning emerge as pivotal driving forces, bridging environmental sustainability and territorial planning strategies. In the basic themes' quadrant, GIS analysis and multi-criteria methods emerge as structural elements in spatial modelling, scenario simulation, and sustainability assessment. Emerging computational frameworks artificial intelligence (AI), machine learning (ML), cloud computing platforms, and GEE significantly optimize geo-indicator-based sustainability assessments. By refining spatial pattern recognition and facilitating enabling large-scale remote sensing data processing, these technologies elevate the efficiency, scalability, and reproducibility of geospatial workflows beyond the capabilities of traditional GIS architectures. Their integration with GIS-based frameworks indicates a growing reliance on advanced computational methods and spatial data analytics for generating robust geo-indicators. These methodologies bolster the objectivity of territorial planning and facilitate a transition toward predictive modeling for sustainable land management. Niche topics, such as land-use monitoring and Bayesian networks, exhibit a high level of internal development, though they are less connected to the rest of the field. Their future evolution could focus on integrating probabilistic models and machine learning techniques to improve the predictive capabilities of territorial models and the accuracy of simulated land-use change scenarios. Finally, environmental indicators and climate adaptation within transition zones constitute burgeoning areas of academic inquiry. This trend anticipates the field's evolution toward integrating territorial planning, scenario analysis, and climate change adaptation, consolidating geo-indicators as key tools for sustainable territorial management and evidence-based decision-making through interdisciplinary collaboration, geospatial analytics, stakeholder engagement, policy integration, and monitoring frameworks across regions.

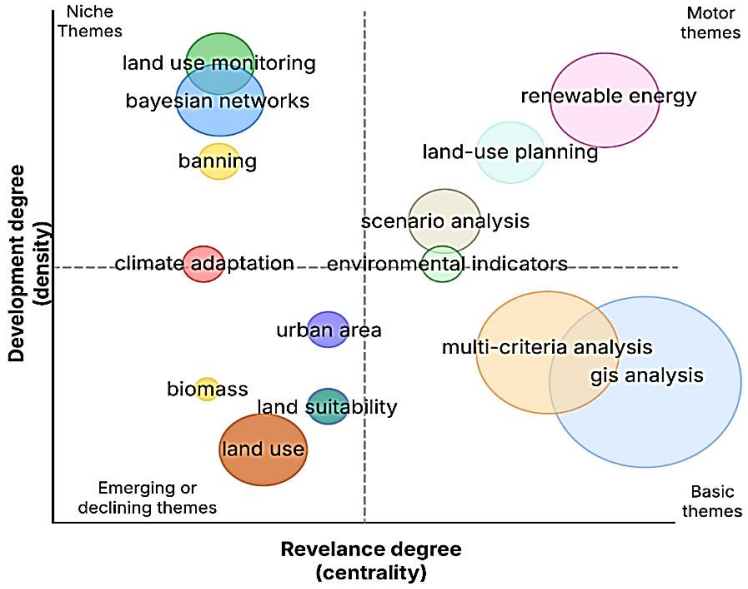

Fig. 7: Bibliometric thematic map of emerging research lines

Systematic review

The systematic review identified 41 studies on geo-indicators of environmental, social, and economic sustainability associated with LULC. These studies were developed across various geographical contexts, including Indonesia, Ecuador, Turkey, China, Egypt, Iran, and Mexico, and cover both urban and rural environments. To map the complexities of territorial sustainability, existing research deploys a broad spectrum of geo-indicators that targeted environmental quality, infrastructure layout, energy efficiency, and public service accessibility.

Prevalence of GIS methods in the study of sustainability geo-indicators

A principal finding of this review underscores the definitive prominence of GIS-based frameworks in synthesizing spatial datasets and executing geospatial analysis of geo-indicators (Fig. 8). In most case studies, these tools enable the integration of geographic information, socio-environmental data, and geoprocessing processes to assess territorial sustainability (Apostolopoulos and Nikolakopoulos, 2021). Among the platforms used, ArcGIS stands out as the most commonly employed tool, although other environments such as TerrSet were also identified, along with decision support methods, including the AHP and fuzzy logic (Chen *et al.,* 2025). Integrating geo-indicators into these platforms facilitates the detection of spatial configurations in land use, thereby aiding in the identification of priority zones for sustainable territorial planning (Jiménez-Espada *et al.,* 2023).

Integration of environmental, social, and economic geo-indicators in sustainable territorial planning

The analysis presented in Table 3 corroborates these findings, identifying critical geo-indicators that drive sustainable territorial management, specifically territorial expansion, biodiversity impacts, composite sustainability indices, and metrics governing agriculture, water, energy, and coastal systems. These indicators reflect the link between land-use planning and objectives such as social equity, balanced regional development, and

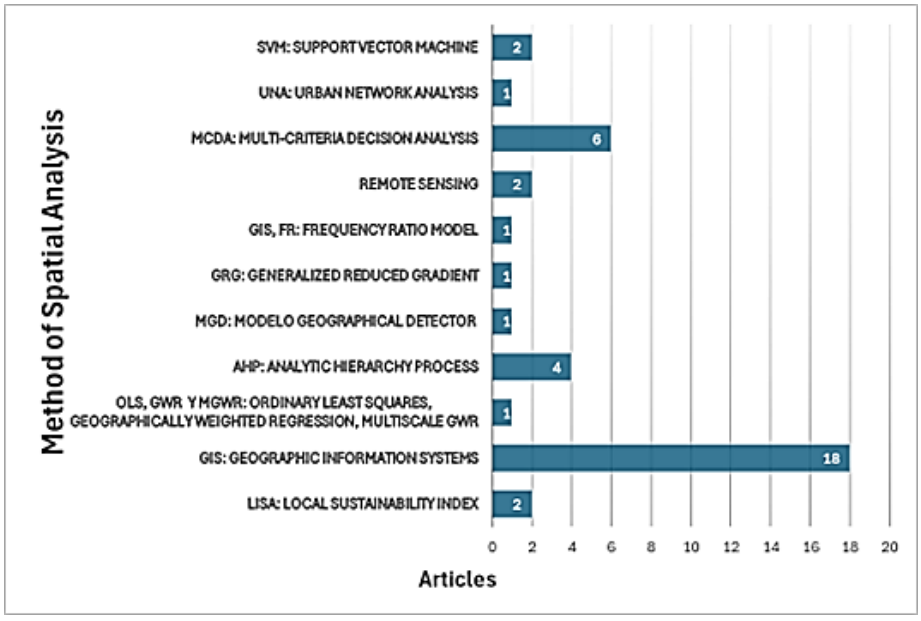

Fig. 8: Distribution of spatial analysis methods in sustainability geo-indicator studies (Analysis of published articles)

Table 3: Geo-indicators for land use sustainability: Impact on territorial management and case studies

Type of geo-indicator (Social = 1, Environmental = 2, Economic = 3)			
Geo-indicator	Impact on sustainable territorial management	Case study	Citation
Territorial expansion	Social equity[1,2]	Socio-spatial aspects and social sustainability	(Akcali and Ispalar Cahantimur, 2023)
	Regional development[3]	Sustainability and spatial heterogeneity in urban agglomerations	(Zhou *et al.*, 2021)
	Sustainable urban optimization[1]	Sustainable urban land-use optimization using multi-criteria decision making (MCDM)	(Arsanjani *et al.*, 2022)
	Expansion control[1]	Methodological approach to sustainable urban densification	(Abdrabo *et al.*, 2021)
	Urban renewal[1]	Analysis of urban spatial compactness and land use mix	(Liu *et al.*, 2023)
	Optimization of urban resources[2]	Spatial decision support for low-carbon cities	(Pignatelli *et al.*, 2023)
	Sustainable urban development[1]	Urban sustainability indicators based on urban grain	(Zhao *et al.*, 2023)
Impact on biodiversity	Interregional balance, social costs[1,2]	Managing spatial sustainability trade-offs in wind power	(Lehmann *et al.*, 2021)
Territorial sustainability index	Sustainable regional development[1,2]	Local sustainability and spatial interdependency	(Pravitasari *et al.*, 2022)
	Urban planning[1,2]	Urban sustainability and fabric typologies	(Calderón *et al.*, 2024)
	Improvement of environmental quality[2]	Optimal weights for urban sustainability	(Vyas *et al.*, 2022)
	Balanced development[1,2]	Spatial analysis of urban sustainability	(Shen and Guo, 2014)
	Sustainable urban development[1,2]	Integrating System Dynamics, GIS, and 3D in urban sustainability	(Xu and Coors, 2012)
	Urban design[1]	Spatial configuration's role in social sustainability and urban density	(Soltani *et al.*, 2022)
	Land use optimization[1,2]	Quantifying sustainability trade-offs in land use	(Bouman *et al.*, 1999)
Rural landscape	Improvement of rural sustainability[2]	Association between multichannel landscape features and rural sustainability	(Meng *et al.*, 2024)

Agricultural sustainability	Agricultural sustainability[2,3]	Energy analysis for sustainability of potato agroecosystems	(Shahhoseini *et al.,* 2022)
	Improves productivity[2]	Land suitability and agricultural sustainability assessment	(Amini *et al.,* 2020)
	Ecological conservation[2]	Geospatial analysis of the federal maritime zone	(Pérez Valdez *et al.,* 2021)
	Risk reduction[2]	GIS-based biomass assessment for sustainable biorefinery	(Sahoo *et al.,* 2016)
	Land management[1,2]	Sustainability indicators for agricultural land use	(Mohamed *et al.,* 2014)
	Food security and climate adaptation[2]	Economic evaluation of crop production in the Ganges region under climate change	(Singh and Dhadse, 2021)
	Land use optimization[1,2]	Framework for analyzing sugarcane agroindustry sustainability	(Aguilar-Rivera, 2019)
	Improvement of agricultural production[2]	Sustainability of wheat production in southwest Iran: Fuzzy-GIS evaluation	(Houshyar *et al.,* 2017)
Coastal sustainability	Territorial planning[2]	Sustainability index for urbanized coasts	(Martínez *et al.,* 2020)
	Risk reduction[1]	Coastal cities and sustainability	(Luengo, 2020)
	Coastal planning[1,2]	Ranking sustainable areas for tidal power plants	(Progênio *et al.,* 2020)
	Integrated coastal management[2]	Coastal sustainability analysis	(Tran *et al.,* 2024)
Infrastructure sustainability	Infrastructure optimization[1]	Automated sustainability assessment of infrastructure using GIS and RS	(Aguilar-Rivera, 2019)
	Road network optimization[1]	Sustainability evaluation of the forest road network using multi-criteria evaluation (MCE)	(Long *et al.,* 2023)
Resource sustainability	Resource optimization[2]	Resources time footprint analysis of wind turbines	(Huang *et al.,* 2023)
Ecological sustainability	Improvement in decision-making[1,2]	Sustainability criteria and cost-benefit analysis: a decision-making framework	(Tiwari, 2000)
Energy sustainability	Resource optimization[1,2]	GIS framework for optimal location and size of biomass energy plants	(Jayarathna *et al.,* 2020)
Water sustainability	Water sustainability[2]	Index-based groundwater sustainability assessment	(Majidipour *et al.,* 2021)
	Improvement of agriculture[2]	Environmental and institutional impacts of tidal river management	(Salam *et al.,* 2021)
	Water resource management[1,2]	Methodology for assessing aquifer sustainability	(Instituto Mexicano de Tecnología del Agua *et al.,* 2023)
	Space use optimization[1]	Geo-spatial multi-criteria evaluation of wave energy in a semi-enclosed sea	(Şan *et al.,* 2021)
	Water use efficiency[2]	Synthetic indicator for sustainability of water resources in agriculture	(Picone *et al.,* 2021)
	Water resource management[2]	Rural water sustainability index (RWSI): a multicriteria and participative approach	(Crispim *et al.,* 2021)

sustainable optimization of urban resources. Geo-indicators such as urban expansion control and renewal contribute to regional development and territorial planning. The use of GIS tools (e.g., ArcGIS and TerrSet) enables more accurate spatial analysis and supports evidence-based decision-making by adapting geo-indicators to specific territorial contexts. This underscores the imperative for unified methodological frameworks to bolster sustainability-oriented territorial management.

Global distribution of GIS tools and application contexts

Fig. 9 illustrates the geographical distribution of the studies included in this systematic review, alongside the specific GIS software platforms utilized across the respective studies. The results reveal that ArcGIS and TerrSet are the most commonly used platforms, although some studies incorporate specific spatial analysis methods, such as ordinary Kriging, and models, such as TRM (Taiwo *et al.,* 2023).

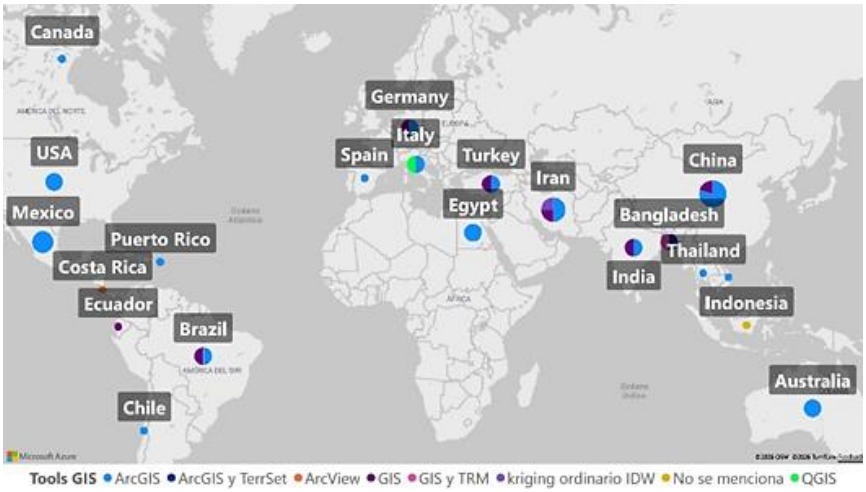

Fig. 9: Geographical distribution of studies on sustainability geo-indicators and the GIS tools used in land use management analysis

The analyzed cases cover a wide variety of territorial contexts, ranging from urban studies in countries such as Mexico, Ecuador, India, and Bangladesh to research conducted in rural areas of Iran and China. This methodological and geographical variations observed across the literature demonstrate that while analytical tools must remain sensitive to local contextual nuances, there is a critical need for unified frameworks capable of cross-referencing environmental, social, and economic geo-indicators (Nagavi *et al.,* 2024).

Identified gaps in literature

This review identifies the absence of a common conceptual framework integrating geo-indicators across environmental, social, and economic dimensions of sustainability. Most studies adopt partial approaches, limiting the understanding of interactions among territorial systems and revealing a significant gap in the literature. This highlights the need for holistic and interdisciplinary frameworks that unify geo-indicators for sustainable territorial planning. Data temporality is another key limitation, as standardized geo-indicator systems are constrained by geographic, institutional, and socioeconomic disparities. Discrepancies between contemporary and legacy datasets compromise the representativeness of geo-indicators, particularly in regions undergoing rapid territorial transformation and acute climate pressures (Mitrică *et al.,* 2021). This underscores the need for updated databases and continuous monitoring systems. Overall, integrated geo-indicator frameworks enable more robust and evidence-based territorial planning than fragmented approaches.

Comparative synthesis of geo-indicators in land use sustainability studies

Fig. 10a synthesizes the conceptual structure of the studies using spatial scale, sustainability domain, indicator type, and spatial data type. Most studies in industrialised countries (60–70%; USA, Canada, Australia, Spain, Germany) focus on national or regional scales, while nearly 50% of studies in middle- and low-income countries (Bangladesh, Iran, Egypt, Mexico) focus on local or urban scales. In terms of sustainability dimensions, about 65% of studies in developed countries integrate environmental, social, and

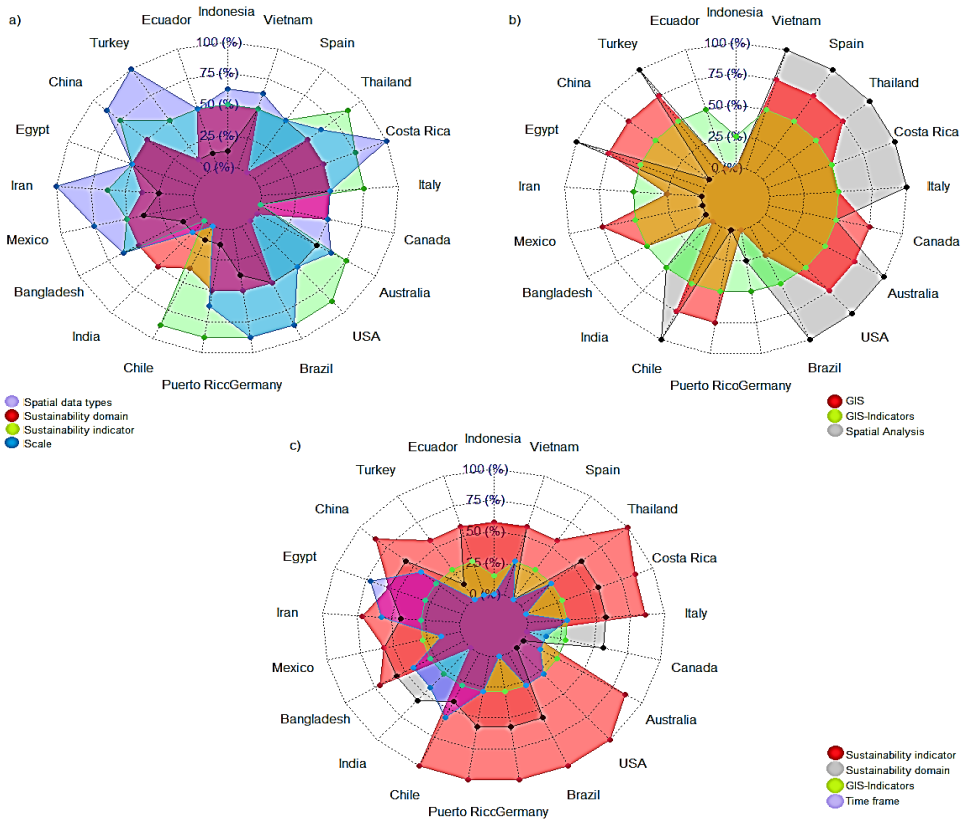

Fig. 10: Integrated Analysis of Indicator Studies. (a) General characterization of the studies, (b) application of spatial methods, and (c) impact and use of geo-indicators

economic aspects, whereas studies in China, Turkey, and Bangladesh are mainly environmental. A corresponding trend manifests across indicator categories, where integrated metrics predominate within developed frameworks (40–60%) whereas environmental or production-oriented indicators remain prevalent in other contexts. Multi-source spatial data is more frequently used in regions with advanced geospatial capacity (30–40%), while other contexts rely mainly on land-use, infrastructure, or RS data.

Fig. 10b reveals significant differences in methodological development based on GIS use, GIS–indicator integration, and spatial analysis methods. Approximately 40–50% of studies in developed countries deploy advanced or hybrid GIS environments, whereas the vast majority of studies in Latin America, Asia, and Africa continues to rely on foundational GIS platforms. A similar pattern appears in GIS–indicator integration, with around 60% of studies in Europe and North America showing high integration levels, compared with less than 20% in Asian and African contexts. Regarding spatial methods, the USA, Australia, and Canada apply predictive models, simulations, and econometric techniques such as Geographically Weighted Regression (GWR) and Multiscale Geographically Weighted Regression (MGWR) (30–40% of studies), whereas Bangladesh, Iran, and Egypt mainly use descriptive spatial analysis or basic multicriteria methods. Correspondingly, Fig. 10c integrates the temporal

dimension of the studies, illustrating significant variations in the analytical depth of the deployed geo-indicators. About 40% of studies in North America and Europe use time series longer than 20 years or include projections, whereas over 70% of studies in countries with lower institutional capacity rely on short time series (<5 years) or do not specify temporal coverage. This gap limits the ability to model long-term territorial dynamics, anticipate future scenarios, and develop geo-indicators for strategic planning. The escalating deployment of geo-indicators underscores the demand for spatially explicit instruments that integrate environmental, social, and economic data, sustained by robust spatial data infrastructures and advanced geospatial analysis (Ahamede and Atumane, 2021). However, the literature remains fragmented, with environmental indicators dominating and social and economic indicators less developed (Maynard *et al.,* 2020). This highlights the need for integrated geo-indicator frameworks to better represent the multidimensional nature of sustainability in territorial planning.

Integration of social and economic dimensions in land use sustainability indicators

A key challenge in land-use sustainability indicators is the dominance of environmental metrics over social and economic dimensions, limiting their ability to capture territorial complexity. Evidence shows that sustainability requires integrating environmental, social, and economic variables for holistic assessment (Malmir *et al.,* 2021). Socio-ecological studies integrate social acceptability and economic viability into spatial models, underscores the critical functions of infrastructural development and credit access in fostering territorial sustainability (Chrisendo *et al.,* 2026; Jiang *et al.,* 2022). Social sustainability research further emphasizes the importance of cultural and socioeconomic factors such as participation and equity (Hellberg, 2023). However, these dimensions remain underrepresented in operational systems, revealing a gap between theory and practice. This uneven development reflects differences in national capacities and indicator production histories. Consequently, the prevailing literature advocates for integrated frameworks that harmonize environmental, social, and economic dimensions to underpin robust geo-indicators tailored for policy formulation and territorial planning. Strengthening consolidated data infrastructures is also essential for improving comparability and validation of indicators.

Limitations of geospatial data and quality for sustainability geo-indicators

The quality and temporal resolution of geospatial data pose a critical challenge for developing reliable geo-indicators to assess land-use sustainability, as measurements based on discontinuous or low-resolution data can yield inaccurate or unrepresentative estimates of real processes (Jiménez-Espada *et al.,* 2023). For instance, urban-scale investigations utilizing GIS and spatial datasets frequently observe that constraints on the availability of open-access, contemporary data restrict both granular spatial analysis and for temporal longitudinal comparisons necessary for rigorous land-use change monitoring (Jiménez-Espada *et al.,* 2023). Furthermore, contemporary literature on geoinformation highlights that different types of satellite data have valuable applications but also present inherent limitations in spatial resolution, temporal frequency, and uniform coverage, which directly affect the accuracy of the indicators generated. These constraints compromise not only ecological and environmental estimates but also the incorporation of socioeconomic variables, which frequently rely on legacy administrative or

census data alongside geospatial imagery (Raffay *et al.,* 2025). Consequently, enhancing the quality, temporal consistency, and accessibility of geospatial data is a necessary methodological step for reinforcing the geo-indicators employed in land use sustainability studies and ensuring that they accurately represent genuine patterns instead of artefacts resulting from incomplete or low-resolution data (Jiménez-Espada *et al.,* 2023).

CONCLUSION

This study demonstrates that geo-indicators are a key approach for assessing land-use sustainability from a spatial perspective. The bibliometric analysis highlights the growing relevance of spatial data, GIS, and advanced modelling techniques in territorial sustainability research. The integration of geo-indicators with spatial analysis tools facilitates the detection of environmental pressures, socio-economic dynamics, and land-use configurations, thereby underpinning evidence-based territorial planning. The systematic review shows that most geo-indicator applications rely on GIS-based methodologies combined with multicriteria decision analysis, spatial modelling, and scenario simulation techniques. These methodologies facilitate the integration of heterogeneous datasets, thereby enabling multi-scalar sustainability assessments. However, the environmental dimension predominates due to the superior availability and standardization of remote sensing and GIS-based datasets. Conversely, socio-economic data exhibit greater heterogeneous and lower spatial consistency, thereby constraining their integration into modelling frameworks.This imbalance highlights the need for more integrated frameworks that unify environmental, social, and economic dimensions into a coherent geo-indicator system. Data temporality and fidelity constitute critical determinants influencing the precision and operational applicability of geo-indicators, particularly amidst rapid territorial transformations and climate variability. A primary limitation of this study stems from its exclusive reliance on the WoS databases, which inherently introduces indexing bias and may omit relevant regional studies. Furthermore, systematic variations in language constraints, indicator definitions, spatial resolutions, and methodological frameworks restrict direct comparability and preclude the execution of a quantitative meta-analysis. Future research should focus on developing standardised geo-indicator frameworks supported by emerging technologies such as cloud-based geospatial platforms, remote sensing big data, and machine learning approaches. Strengthening interoperability, harmonising methodological standards, and promoting institutional collaboration are essential to enable large-scale implementation of geo-indicators for sustainable land-use planning.

AUTHOR CONTRIBUTIONS

D. Freire-Granda contributed to the conceptualisation, research, formal analysis, methodology, software, drafting of the original document, project management, and supervision. A. Velastegui-Montoya contributed to the study, methodology, and drafting of the original document. A.M. Meiguins de Lima contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. M. Adami contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. A.D. Ramirez contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. P. Escandón-Panchana contributed to

the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
AHP	Analytical hierarchy process
DOI	Digital object identifier
DPSIR	Driving forces–pressures–state–impact–response
ESPOL	Escuela superior politécnica del litoral
FR	Frequency Ratio
GEE	Google earth engine
GIS	Geographic information system
GIS-MCDM	Geographic information system–multi-criteria decision making
GIS-MCE	Geographic information system–multi-criteria evaluation
GRG	Generalized reduced gradient
GWR	Geographically weighted regression
JBMUR	Jakarta–bandung mega urban region
KPIs	Key performance indicators
LSI	Local sustainability index
LULC	Land use and land cover
MA	Millennium ecosystem assessment
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
MCE	Multi-criteria evaluation
MGD	Geographical detector model
MGWR	Multiscale geographically weighted regression
OLS	Ordinary least squares
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
QGIS	Quantum geographic information system
RS	Remote sensing
RStudio	an integrated development environment for R programming

RWSI	Rural water sustainability index
SDGs	Sustainable development goals
SEEA	System of environmental-economic accounting
SVM	Support vector machine
UN	United Nations
WoS	Web of Science

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