

Article

Generative Artificial Intelligence in Geography: Structure and Evolution of an Emerging Field

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Abstract

Generative artificial intelligence (GenAI) is increasingly applied across geographic research, yet existing studies remain fragmented and lack a field-level synthesis. This study addresses this gap through a bibliometric analysis of 891 peer-reviewed journal articles published between 2022 and 2025 and indexed in Scopus. The results indicate a rapid expansion of GenAI-related geographical research following the diffusion of large language models, alongside strong spatial concentration in a small number of countries and institutions. Five major research themes are identified, including LLM-based GeoAI and GIS workflows, Earth observation and remote sensing, knowledge-driven urban analytics, educational and scholarly communication contexts, and tool-oriented geospatial platforms. Temporal patterns suggest a shift from early exploratory studies toward workflow-level integration. Highly cited contributions concentrate in education, remote sensing, and GIScience, while intellectual foundations draw on both foundational AI architectures and long-standing geographic measurement and modeling. By providing a systematic and large-scale mapping of the structure and evolution of GenAI in geography, this study extends beyond existing narrative and application-focused reviews and offers an integrated account of the field's development. It also identifies key research gaps for future research.

Keywords: bibliometric analysis; large language model (LLM); generative artificial intelligence (GenAI); geographical research; geographic information science (GIScience)



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1. Introduction

Artificial intelligence (AI) has become a central driver of transformation across geographic research, reshaping how spatial data are generated, analyzed, and interpreted [1]. Over the past decade, advances in machine learning and deep learning have substantially expanded the analytical capacity of geography, particularly in fields such as geographic information science (GIScience), remote sensing, environmental modeling, and urban studies [2]. More recently, the emergence of generative artificial intelligence (Generative AI, or GenAI) has marked a qualitative shift in this trajectory [3]. Generative AI refers to a family of computational models capable of producing statistically novel outputs that resemble existing data, including images, text, and complex spatial patterns [4]. In contrast to earlier generations of AI that primarily focused on rule-based reasoning or discriminative prediction, GenAI models are designed to generate new data, representations, and narratives, opening new possibilities for geographic knowledge production [5]. This shift raises important questions about how GenAI is being adopted in geography, as a discipline.

Geographic phenomena often involve incomplete observations, uncertain boundaries, and multiscalar interactions, making generative approaches attractive for tasks such as spatial data augmentation, downscaling, scenario generation, and the integration of spatial and textual information [6]. Consequently, applications of GenAI have rapidly proliferated across multiple subfields of geography. In physical and environmental geography, generative models have been employed to enhance remote sensing imagery, simulate land cover change, and generate high-resolution climate or environmental datasets from sparse observations [7,8]. In human and urban geography, GenAI has been applied to urban form simulation, mobility pattern modeling, and the analysis of place-based narratives derived from large-scale textual data [9]. Within GIScience and cartography, generative techniques support automated map production, spatial data imputation, and novel forms of geovisualization and storytelling [5].

Despite the growing body of work, the literature on GenAI in geography remains fragmented. Most studies focus narrowly on specific methods, datasets, or application domains, and are scattered across a wide range of journals in geography, computer science, environmental science, and urban studies [3]. Although several narrative reviews have examined GenAI applications in geography (e.g., [10,11]), these reviews typically draw on a relatively small corpus of studies. As a result, their conclusions often rely on selective synthesis and the qualitative interpretation of individual authors. In contrast, a limited number of systematic reviews have focused on particular geographical subfields, such as geographical information science [12], remote sensing and regional studies [13], or urban planning (e.g., [14]). While these reviews provide valuable insights, they tend to prioritize technical performance or domain-specific outcomes rather than examining the overall structure and evolution of the research field. Consequently, it remains unclear how GenAI research in geography has developed over time, and limited attention has been paid to identifying its dominant themes.

Bibliometric analysis offers a powerful means to address these limitations. By quantitatively analyzing large bodies of scientific literature, bibliometric methods enable the systematic mapping of research performance, thematic evolution, and intellectual and collaborative networks, thereby providing a macro-level perspective on knowledge production [15]. Applying a bibliometric perspective to the study of GenAI in geography is timely for several reasons. First, the rapid pace of methodological innovation, particularly following the release and subsequent widespread adoption of large language models such as ChatGPT in 2022, has driven a sharp increase in relevant publications in recent years [4,16]. This growth is evident in applied studies that employ LLMs for geospatial tasks and workflows, including geographic information system (GIS) and geospatial-domain LLM development [17], geospatial code generation and tool use [18], and natural language-driven mapping and cartographic design [19]. It is also reflected in benchmark and evaluation studies that examine the limitations of LLMs in spatial cognition, spatial reasoning, and geospatial task performance [20]. Second, the interdisciplinary nature of GenAI research poses additional challenges, as relevant studies are often embedded within broader AI, data science, or domain-specific outlets rather than being explicitly framed as geographical research. A comprehensive bibliometric analysis can help clarify how these issues are addressed, or overlooked, within the existing literature.

Against this background, this study aims to provide a systematic bibliometric review of research on the applications of Generative AI in geography, with a focus on geography as a disciplinary core while also incorporating the broader geospatial research domains, including GIScience, remote sensing, and urban studies. Specifically, the study seeks to map the knowledge structure of this emerging field, identify major research themes and their temporal evolution, examine the intellectual foundations and collaborative networks under-

pinning the literature, and highlight emerging trends and research gaps. Methodologically, the analysis combines performance indicators with science mapping techniques, including co-word analysis (to identify themes and their evolution), and co-citation analysis (to trace intellectual foundations). By doing so, the paper offers a timely synthesis of the recent phase of GenAI adoption in geography, providing a systematic and large-scale mapping of the field's development, structure, and intellectual organization that extends beyond existing case-based and domain-specific reviews. This study therefore contributes a clearer understanding of how GenAI is reshaping geographic research. The findings can inform future methodological development, interdisciplinary collaboration, and critical reflection on the role of generative technologies in the production of geographic knowledge.

2. Literature Review

2.1. *The Evolution of AI and Geographic Research*

The application of artificial intelligence in geography predates the recent surge of interest in Generative AI and can be traced back to early efforts in expert systems, spatial decision support, and rule-based modeling within GIS [21]. These early approaches sought to formalize geographic reasoning and support planning and management tasks but were constrained by limited computational power and rigid knowledge representations [3]. With the expansion of digital spatial data and advances in computing, machine learning techniques began to play a more prominent role in geographic research, enabling data-driven classification, clustering, and prediction across a wide range of spatial problems [1].

The rise of deep learning marked a significant turning point in this evolution. Convolutional neural networks, recurrent neural networks, and related architectures demonstrated strong performance in tasks such as image classification, object detection, and sequence modeling, which translated naturally to remote sensing, spatial pattern recognition, and spatiotemporal forecasting [22]. This period saw the consolidation of what is often referred to as geospatial artificial intelligence (GeoAI), a research paradigm that integrates AI techniques with spatial science to address complex geographic questions [23]. While most deep learning applications remained fundamentally discriminative, focusing on labeling or predicting known variables, they laid the methodological and conceptual groundwork for the subsequent adoption of generative approaches [24].

Generative AI extends this trajectory by shifting the analytical emphasis from prediction to synthesis [25]. Rather than inferring outputs from inputs within predefined categories, generative models aim to learn the underlying data-generating processes and produce new, plausible instances of geographic data [5]. This distinction is particularly consequential for geography, where incomplete data coverage, scale mismatches, and uncertainty are persistent challenges [10].

As a result, generative models have increasingly been explored as tools not only for improving predictive accuracy but also for expanding the representational and exploratory capacities of geographic analysis. In the post-2022 period, a substantial share of this momentum has been associated with LLM- and Generative Pre-trained Transformer (GPT)-based systems, which have rapidly diffused into GIScience and geography-facing outlets and have catalyzed new workflows for interacting with geospatial data using natural language [17,26–28].

Among generative techniques, generative adversarial networks (GANs) have been the most widely adopted in geographic research to date. GANs consist of a generator and a discriminator trained in opposition, enabling the generation of highly realistic synthetic data [29]. In geography, GANs have been extensively applied to remote sensing and Earth observation, including tasks such as super-resolution of satellite imagery, cloud removal, land cover synthesis, and cross-sensor data translation [30]. These applications highlight

the capacity of GANs to address spatial resolution gaps and data scarcity, particularly in regions where high-quality observations are limited.

More recently, LLMs and multimodal foundation models represent a further expansion of generative capabilities relevant to geography. LLMs are capable of processing and generating natural language at scale, enabling applications such as geographic knowledge extraction, place name disambiguation, spatial reasoning over text, and the synthesis of place-based narratives [21,31]. Since 2022, LLM-centered work has become a particularly visible strand in GIScience and geography-facing research, partly because terms such as “LLM”, “GPT”, and “ChatGPT” are frequently used in titles, abstracts, and keywords to describe new geospatial LLM frameworks, applications, and evaluations [17,26–28]. When combined with visual and spatial inputs, multimodal models facilitate the integration of maps, images, and text, opening new avenues for geovisualization, cartographic communication, and human–computer interaction in geographic research. Recent GIScience-oriented contributions include GIS-specific or GeoAI-oriented LLM frameworks [17] and agenda-setting discussions of opportunities and challenges for integrating LLMs with GIScience concepts and methods [28]. LLM-based systems have also been explored for natural language interaction with geospatial data through task-decomposing and tool-using workflows [32]. In cartography and geovisualization, LLMs have been used to support natural language-driven map design workflows that reduce technical barriers while preserving cartographic constraints [19]. Alongside these applications, evaluation work has begun to benchmark the limits of LLMs for spatial cognition, spatial reasoning, and geospatial task performance, which is central to assessing when LLM outputs can be trusted for geographic analysis [20]. These developments challenge traditional distinctions between quantitative and qualitative approaches, suggesting a more integrative future for geographic inquiry.

2.2. Applications of GenAI in Geography

The application of Generative AI spans multiple domains within geography, reflecting the discipline’s diversity and interdisciplinarity. In physical and environmental geography, generative models are commonly used to enhance observational data and support environmental modeling. Applications include the generation of high-resolution climate datasets, simulation of land surface processes, and reconstruction of missing or degraded remote sensing imagery [7,8]. By augmenting empirical observations, GenAI enables more detailed analysis of environmental change and supports modeling efforts in data-scarce contexts.

In human and urban geography, generative approaches have been applied to the modeling of urban form, transportation networks, and human mobility patterns. Urban simulation studies employ generative models to explore alternative development scenarios, assess infrastructure impacts, and visualize potential futures of cities [9]. Text-based generative models have also been used to analyze large corpora of social media data, planning documents, and historical texts, facilitating the study of place perception, socio-spatial narratives, and collective memory [33]. These applications underscore the potential of GenAI to bridge spatial analysis with social and cultural dimensions of geography. Compared with remote sensing, this literature may be more methodologically heterogeneous, combining simulation-oriented studies with language-centered analyses that draw from computational social science and digital humanities.

Within GIScience and cartography, Generative AI has contributed to advances in automated mapping, spatial data imputation, and geovisual analytics. Generative techniques support the creation of maps and visual representations tailored to specific users or contexts, as well as the synthesis of spatial datasets that integrate multiple sources and scales [5]. These developments align with broader trends toward user-centered GIS and interactive geovisualization, where generative models can dynamically adapt representa-

tions to analytical needs [34]. Because GIScience sits between domain applications and methodological development, it may act as a bridging cluster linking environmental, urban, and human-centered strands of GenAI research.

Across these domains, the adoption of Generative AI reflects both technological opportunity and methodological experimentation. However, applications remain unevenly distributed, with a strong concentration in remote sensing and environmental modeling and comparatively fewer studies in qualitative, critical, or participatory geographic research [35]. This imbalance makes field-wide mapping important, both to identify underrepresented themes and to clarify whether ethical and epistemological debates are integrated into mainstream application-oriented research or remain siloed.

3. Methodology

3.1. Data Collection

This study ensures transparent and replicable retrieval of bibliographic data by according to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Figure 1). It operationalized through three sequential steps: identification, screening, and inclusion [36].

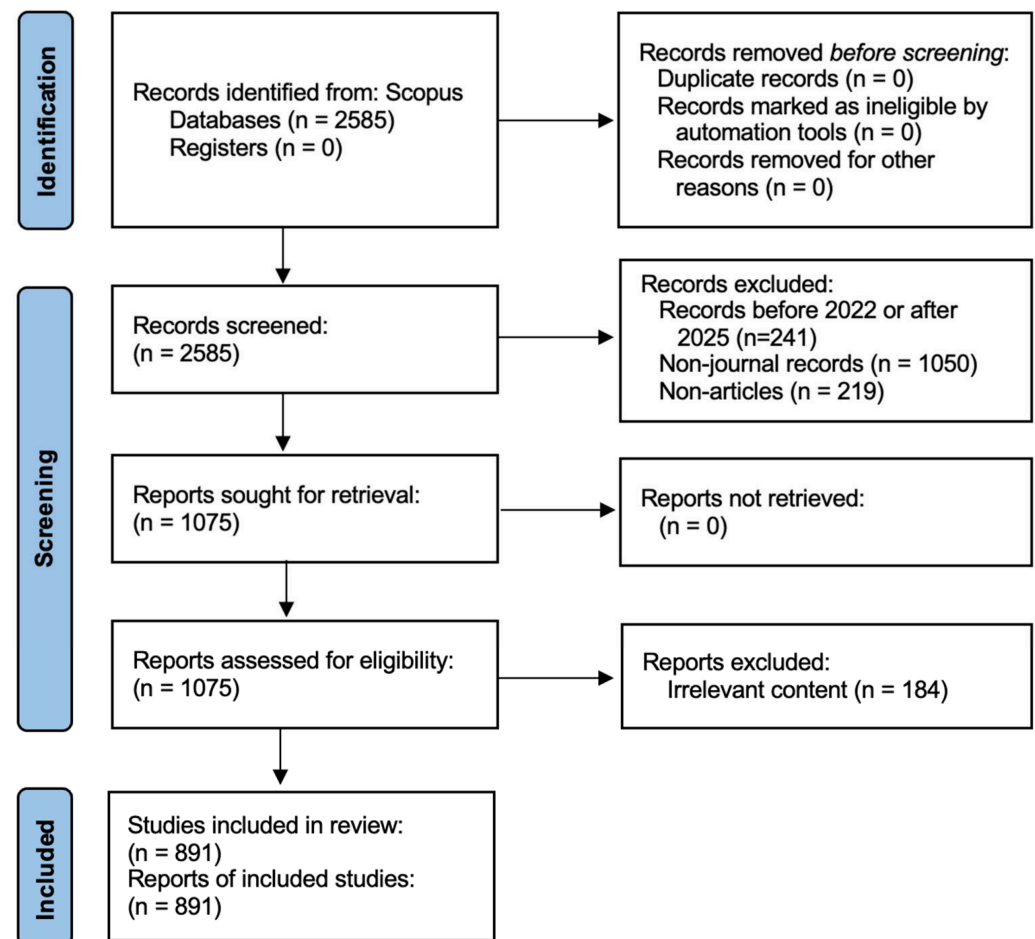


Figure 1. Literature selection process following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

Identification of literature corpus was achieved by searching relevant documents in Scopus. Although Scopus and Web of Science (WoS) are widely recognized as leading bibliographic databases for bibliometric studies, Scopus was selected as the sole data source for three reasons. First, the two databases substantially overlap in many domains, but

Scopus typically provides broader coverage of peer-reviewed journals across geography, GIScience, urban studies, environmental science, and adjacent interdisciplinary outlets. This feature is advantageous for interdisciplinary topics whose outputs are dispersed across multiple fields rather than concentrated in a small set of core journals [37]. Second, differences in indexing practices and metadata structures across Scopus and WoS can introduce heterogeneity when datasets are merged. Using a single, internally consistent database therefore improves transparency and interpretability for field-level mapping [38]. Third, focusing on one database simplifies the replication of the search and screening process.

The data query was executed on 5 January 2026 using Boolean logic and two blocks of relevant keywords: TITLE-ABS-KEY (("generative AI" OR GenAI OR "generative artificial intelligence" OR "large language model*" OR LLM* OR "Generative Pre-trained Transformer*" OR ChatGPT OR "GPT-5" OR "GPT5" OR "GPT-4" OR GPT4 OR "GPT-3.5" OR GPT3.5 OR "GPT-3" OR GPT3) AND (geograph* OR geospatial OR "spatial data" OR "geographic information syste*" OR GIS OR cartograph* OR "remote sensing" OR "earth observation" OR GIScience OR GeoAI OR geovisualization OR urban* OR "land use" OR "land cover")).

This keyword string was designed to retrieve documents that explicitly connect Generative AI with geographic or geospatial research, thereby capturing both geography-focused studies and related geospatial research domains that contribute to geographic knowledge production. The first keyword block operationalizes the Generative AI discourse by combining model-agnostic umbrella terms (e.g., "generative AI", "GenAI") with high-frequency indexing terms related to large language models (e.g., "large language model*", "GPT", "ChatGPT"), which reflect the dominant vocabulary used to describe post-2022 GenAI research in geography-facing outlets and provide a clear and replicable operational boundary for the dataset. The second block combines disciplinary terms (e.g., geograph*, GIScience, cartograph*) with application anchors (e.g., remote sensing, earth observation, land use/cover, urban) to capture the cross-disciplinary distribution of GenAI research.

Screening was implemented in two stages. First, database filters were applied to restrict records to the target time window, source type, and document type. Specifically, publication years were limited to 2022–2025 (filter command: PUBYEAR > 2021 AND PUBYEAR < 2026), reflecting the recent proliferation of GenAI technologies associated with the emergence and diffusion of LLMs. Only journal publications were retained (filter command: LIMIT-TO (SRCTYPE, "j")) to ensure peer-reviewed scholarly content and to reduce inconsistencies in indexing coverage and metadata completeness that are common for conference papers, book chapters, and other non-journal outputs. To capture original research, only research articles were retained (filter command: LIMIT-TO (DOCTYPE, "ar")). Second, duplicate records were removed by comparing DOIs and, where DOIs were missing, by matching titles and author names to identify overlapping entries. Screening also included an eligibility check based on title and abstract review to ensure that retained studies explicitly focus on generative AI methods and are relevant to geographic or geospatial research contexts. Records were excluded if they focused on non-generative AI approaches or lacked a clear spatial or geographic component. After screening, 891 articles were included for bibliometric analysis.

3.2. Data Analysis and Visualization

Prior to bibliometric mapping, the dataset was cleaned manually based on a pre-defined set of normalization rules applied consistently across the dataset. Cleaning focused on harmonizing inconsistencies and reducing artificial fragmentation caused by variant labels, including country variants (e.g., UK/United Kingdom, USA/United States), spelling differences, plural versus singular forms, hyphenation, and abbreviations (e.g.,

GIS vs. geographic information systems). The cleaning process ensured the validity of network structures derived from author keywords, indexed keywords, affiliations, and country fields.

To explore the structure and evolution of Generative AI research in geography, this study applies a combination of performance analysis and science mapping techniques, following established bibliometric approaches [39]. Performance analysis provides an overview of publication trends and research productivity. Key indicators include annual publication output, leading journals, and the most productive authors and countries. These indicators provide a descriptive foundation for understanding the growth and distribution of GenAI research within geography.

Science mapping examines the structure and dynamics of a scientific field using network-based bibliometric techniques [15]. Specifically, co-occurrence analysis of keywords to map thematic structure based on keyword co-occurrence patterns, and co-citation analysis to identify intellectual bases based on co-cited references or sources, respectively.

All analyses and visualizations were performed using VOSviewer (version 1.6.20) [40]. In the visualizations, nodes represent bibliographic items (e.g., keywords, documents, sources, or countries). Node size reflects the magnitude of an attribute (e.g., frequency or citations), link thickness indicates relationship strength (e.g., co-occurrence or coupling strength), and spatial proximity reflects relatedness. VOSviewer's clustering algorithm groups items into clusters that support interpretation of themes and intellectual communities. Threshold values and clustering configurations were determined through iterative testing to balance network coverage and interpretability. Lower thresholds increase network density but may reduce clarity due to overlapping clusters, whereas higher thresholds improve separation but may exclude relevant items. The selected configuration provides a clear and interpretable clustering structure while retaining sufficient representation of the dataset. Cluster solutions generated under different parameter settings were inspected to ensure that the main thematic patterns remained stable and substantively meaningful.

4. Results

4.1. Publication Outputs

Figure 2 illustrates the annual distribution of journal articles on GenAI and geography from 2022 to 2025. Publication output shows a clear and rapid growth trajectory over these four years, with an annual growth rate exceeding 300 percent, indicating the swift emergence and consolidation of GenAI as a research focus within the geographical sciences. In 2022, only 11 GenAI-related articles were published, increasing to 45 in 2023 and 204 in 2024, before reaching a peak of 631 articles in 2025. Cumulatively, 835 articles, representing 93.7 percent of the dataset, were published during the final two years.

This publication pattern indicates that the field did not evolve through gradual methodological diffusion, but rather through rapid uptake triggered by the public release and subsequent stabilization of large language models and multimodal generative systems. Compared with earlier waves of artificial intelligence applications in geography during the 2000s and 2010s, which unfolded over a longer period and diffused incrementally across subfields such as remote sensing and spatial analysis [11,41], the GenAI-related literature exhibits a markedly accelerated adoption cycle. This pattern suggests that GenAI entered geography not as an incremental extension of existing tools, but as a set of broadly accessible systems that lowered technical barriers for experimentation and application.

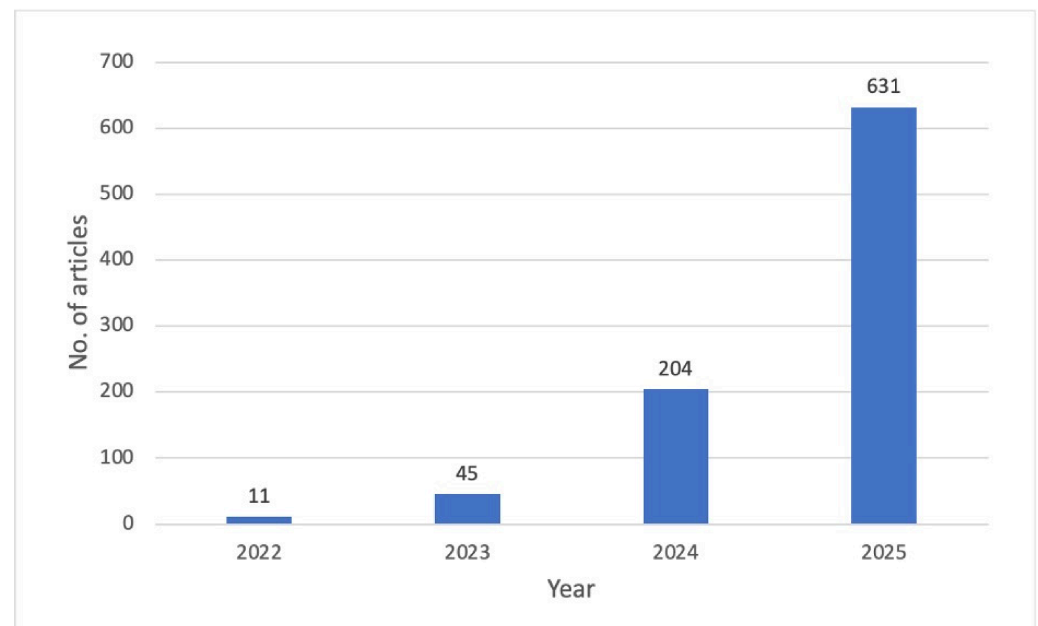


Figure 2. Number of articles on GenAI and geography research.

Spatially, publication output is highly uneven (Figure 3). China contributes 364 articles, accounting for 40.9 percent of the total corpus, followed by the United States with 201 articles (22.6 percent). The United Kingdom ranks third with 64 articles (7.2 percent), while Germany (43 articles, 4.8 percent), Spain (38 articles, 4.3 percent), Canada (35 articles, 3.9 percent), and Australia (33 articles, 3.7 percent) form a second tier of contributing countries. Together, China and the United States account for 565 articles, equivalent to 63.4 percent of all publications, indicating a strong concentration of GenAI-related geographic research within these two national research systems. A broader group of countries contributes more modest outputs, typically between 10 and 31 articles each, including Saudi Arabia, South Korea, India, Italy, Hong Kong, Singapore, Japan, France, the Netherlands, Poland, the United Arab Emirates, Malaysia, Switzerland, Brazil, Taiwan, Austria, the Czech Republic, New Zealand, and Turkey. This distribution reflects a long-tailed pattern in which a small number of countries dominate publication output while a larger set of countries participate at lower levels.

The institutional distribution mirrors the country-level pattern (Table 1). Among the 18 institutions with at least 10 publications, 14 are located in China, two in the United States, one in Germany, and one in Hong Kong. Wuhan University leads with 42 articles, followed by the Chinese Academy of Sciences with 30 and Tsinghua University with 22. Additional high-output Chinese institutions include the University of Chinese Academy of Sciences, the Ministry of Education of the People’s Republic of China, China University of Geosciences, Beihang University, Peking University, Tongji University, Zhejiang University, Southeast University, and several national research institutes. Outside China, the University of Hong Kong records 15 articles, while the Massachusetts Institute of Technology and Texas A&M University contribute 14 and 11 articles, respectively. Technische Universität München represents the highest-output European institution with 11 articles. The concentration of leading institutions within China and the United States corresponds closely to their dominant shares of national publication output, indicating that country-level prominence is driven by a relatively small number of high-productivity universities and research organizations rather than a diffuse institutional base. Affiliation counts are based on full counting of author affiliations as indexed in Scopus, a common practice in bibliometric performance analysis.

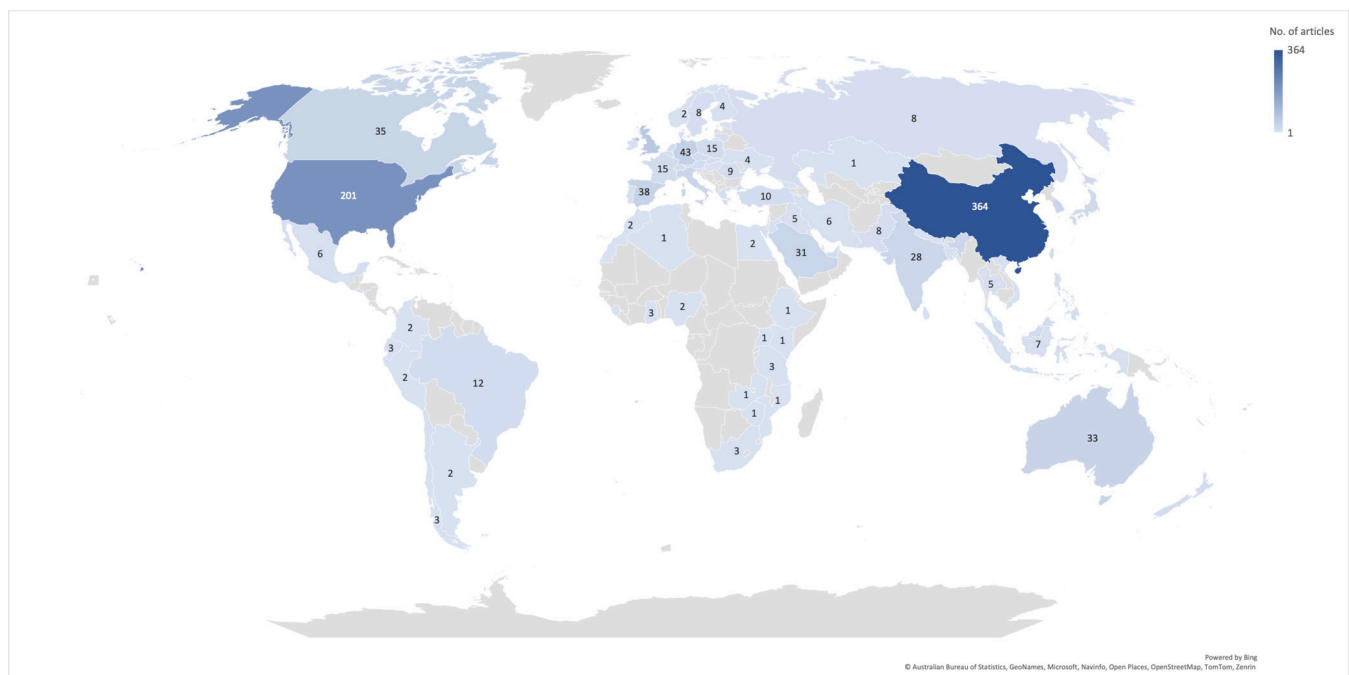


Figure 3. Number of articles on GenAI and geography research (Note: numbers and colors shown on the map indicate the number of articles contributed by each country or territory. The map was created using Microsoft Excel for Mac, Version 16.78.3 (Microsoft Corporation, Redmond, WA, USA).).

Table 1. Productive institutes on GenAI and geography research.

Rank (nth)	Institute ¹	Country/Territory	Articles
1	Wuhan University	China	42
2	Chinese Academy of Sciences	China	30
3	Tsinghua University	China	22
4	University of Chinese Academy of Sciences	China	20
5	Ministry of Education of the People's Republic of China	China	19
6	China University of Geosciences	China	17
7	Beihang University	China	16
8	Peking University	China	16
9	The University of Hong Kong	Hong Kong	15
10	Massachusetts Institute of Technology	United States	14
11	State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing	China	14
12	Tongji University	China	12
13	Aerospace Information Research Institute	China	12
14	Southwest Jiaotong University	China	11
15	Technische Universität München	Germany	11
16	Texas A&M University	United States	11
17	Zhejiang University	China	10
18	Southeast University	China	10

¹ Only the institutes with at least 10 articles are listed.

4.2. Subject Areas

The subject-area distribution of GenAI-related geographical research reveals an overall pattern characterized by a strong computational and methodological core, complemented by substantial engagement from Earth and environmental sciences and a parallel expansion into socio-spatial domains (Table 2). Among all subject areas, Computer Science (368 articles, 41.3 percent), Social Sciences (352, 39.5 percent), and Engineering (294, 33.0 percent)

account for the largest shares of publications, indicating that the field is driven by the convergence of algorithm development, applied system design, and socio-spatial inquiry. This subject-area dominance is reflected in the journals that publish the largest numbers of GenAI-related geographical studies (Table 3). The most productive outlets, including IEEE Transactions on Geoscience and Remote Sensing (29 articles), ISPRS International Journal of Geo-Information (29), and the International Journal of Geographical Information Science (22), are boundary-spanning journals that primarily align with the Computer Science and Engineering subject areas while also incorporating applications from Earth and Planetary Sciences, particularly through geospatial computation and remote sensing research.

Table 2. Subject areas of articles on GenAI and geography research.

Rank (nth)	Subject Area ¹	Article ²	%
1	Computer Science	368	41.3
2	Social Sciences	352	39.5
3	Engineering	294	33.0
4	Earth and Planetary Sciences	235	26.4
5	Environmental Science	120	13.5
6	Business, Management and Accounting	67	7.5
7	Arts and Humanities	47	5.3
8	Physics and Astronomy	47	5.3
9	Materials Science	44	4.9
10	Mathematics	40	4.5
11	Energy	35	3.9
12	Decision Sciences	33	3.7
13	Agricultural and Biological Sciences	30	3.4
14	Economics, Econometrics and Finance	24	2.7
15	Medicine	23	2.6
16	Psychology	20	2.2
17	Chemical Engineering	17	1.9

¹ Only the subject areas with more than 15 articles are listed; ² The total count is larger than the total number of articles because some belong to more than one subject area.

Table 3. Productive journals on GenAI and geography research.

Rank (nth)	Journal ¹	Articles
1–2	IEEE Transactions on Geoscience and Remote Sensing; ISPRS International Journal of Geo Information	29
3	International Journal of Geographical Information Science;	22
4	IEEE Access;	20
5	Remote Sensing Applied Sciences Switzerland	17
6–9	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing; ISPRS Journal of Photogrammetry and Remote Sensing; International Journal of Digital Earth	13
10–12	Computers Environment and Urban Systems; Journal of Geo Information Science; Sustainable Cities and Society Buildings;	10
13–16	IEEE Geoscience and Remote Sensing Letters; IEEE Transactions on Intelligent Transportation Systems; International Journal of Applied Earth Observation and Geoinformation	9

Table 3. Cont.

Rank (nth)	Journal ¹	Articles
17–19	Applied Soft Computing; Sustainability Switzerland; Transactions in GIS	8
20	Smart Cities Cities;	7
21–26	Environment and Planning B Urban Analytics and City Science; Humanities and Social Sciences Communications; IEEE Geoscience and Remote Sensing Magazine; International Journal of Architectural Computing; Land	6
27–28	Analysis and Metaphysics; IEEE Communications Magazine	5

¹ Only journals that have at least 5 articles are shown.

Beyond this computational core, the notable contributions of Earth and Planetary Sciences (235 articles, 26.4 percent) and Environmental Science (120, 13.5 percent) are further evidenced by the concentration of publications in journals specializing in Earth observation and environmental analysis. Journals such as Remote Sensing (17 articles), ISPRS Journal of Photogrammetry and Remote Sensing (13), and IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (13) indicate that GenAI methods are being actively integrated into environmental monitoring, Earth system modeling, and spatial analysis workflows. This alignment suggests that GenAI adoption has been particularly rapid in research contexts where large-scale spatial data and computational experimentation were already well established [8].

The substantial share of Social Sciences (352 articles, 39.5 percent) is also reflected in the presence of productive journals oriented toward urban systems, planning, and socio-spatial analytics. Outlets such as Computers, Environment and Urban Systems (10 articles), Sustainable Cities and Society (10), Smart Cities (7), Cities (6), and Environment and Planning B: Urban Analytics and City Science (6) provide publication venues for GenAI applications in urban governance, spatial decision-making, and policy analysis. Their prominence indicates that GenAI is increasingly being used to support analytical work on social and institutional processes in geography, particularly in contexts where textual, policy, and mixed-method data are central [34].

Smaller but still visible subject-area contributions, including Business, Management and Accounting (67 articles, 7.5 percent) and Arts and Humanities (47, 5.3 percent), are mirrored by the appearance of multidisciplinary and application-oriented journals, such as Applied Sciences (13 articles), Sustainability (8), Land (6), Buildings (9), and Humanities and Social Sciences Communications (6). These journals tend to accommodate cross-cutting and practice-oriented research, suggesting that GenAI is beginning to diffuse into applied sustainability, planning, design, and interpretive geographical studies, although these strands remain secondary relative to the dominant computational, Earth science, and socio-spatial domains.

4.3. Keywords

The frequency distribution of keywords highlights the dominant concepts and methodological emphases in GenAI-related geographical research (Table 4). Overall, the results indicate that the field is currently structured around large language models and generative AI techniques, closely linked to remote sensing and GIS, with growing attention to semantic analysis, decision-making, and urban applications.

Table 4. Frequently occurring keywords on GenAI and geography research.

Rank (nth)	Keyword ¹	Occurrence
1	Large Language Model	452
2	Artificial Intelligence	294
3	Language Model	269
4	Remote Sensing	220
5	Generative AI	163
6	Machine Learning	98
7	ChatGPT	97
8	Natural Language Processing	86
9	Semantics	79
10	Decision Making	70
11	Geographic Information Systems	67
12	Deep Learning	65
13	Urban Planning	63
14–15	Computational Linguistics	53
16	Spatial Analysis	53
17–18	Multi-modal Data Set	52
19	Visual Languages	50
20	Information Management	49
21	Learning Systems	48
22–23	Numerical Model	46
	Image Analysis	44
	Knowledge Graph	44

¹ Only the keywords that have at least 100 occurrences are shown.

The most frequently occurring keyword is “Large Language Model” (452 occurrences), followed by “Artificial Intelligence” (294) and “Language Model” (269). This pattern reflects the central role of transformer-based language models in driving recent GenAI research, particularly since the public release of large-scale models that enabled broad experimentation across disciplines [42]. The co-presence of general AI terms and specific model-related keywords suggests that the literature spans both conceptual discussions of AI and applied studies focused on LLM-based methods in geographical contexts.

The high frequency of “Remote Sensing” (220) indicates that GenAI has been rapidly integrated into one of geography’s most data-intensive subfields. This aligns with earlier trajectories in which machine learning and deep learning methods were first adopted in remote sensing due to the availability of large-scale imagery and established computational pipelines [7]. Related keywords such as “Machine Learning” (98) and “Deep Learning” (65) suggest continuity with earlier AI applications, even as research attention shifts toward generative approaches.

Keywords associated with language and semantic processing, including “Natural Language Processing” (86), “Semantics” (79), “Computational Linguistics” (53), and “Knowledge Graph” (44), indicate increasing interest in extracting and structuring spatial knowledge from textual and multimodal sources. This points to a growing role for GenAI in interpretive and meaning-oriented geographical analysis, beyond numerical and image-based tasks [43].

Application-oriented keywords further illustrate how GenAI is being embedded within established geographical practices. “Geographic Information Systems” (67) and “Spatial Analysis” (53) suggest integration with core analytical frameworks, while “Decision Making” (70) and “Urban Planning” (63) indicate applied use in policy-relevant and urban

contexts [2]. Finally, keywords such as “Multi-modal” (52) and “Image Analysis” (44) highlight growing attention to combining textual, visual, and numerical data within unified analytical workflows, a defining feature of contemporary GenAI systems [33].

To examine thematic associations beyond individual keyword frequencies, a co-occurrence analysis was conducted on 29 keywords that appeared at least seven times. In the network visualization (Figure 4a), the most prominent nodes are “large language model,” “GenAI,” “AI,” and “ChatGPT,” which appear with high frequency and occupy central positions in the network, indicating extensive ties with multiple keyword groups. The resulting network groups these keywords into five clusters, each representing a distinct but partially overlapping thematic concentration within GenAI-related geographical research.

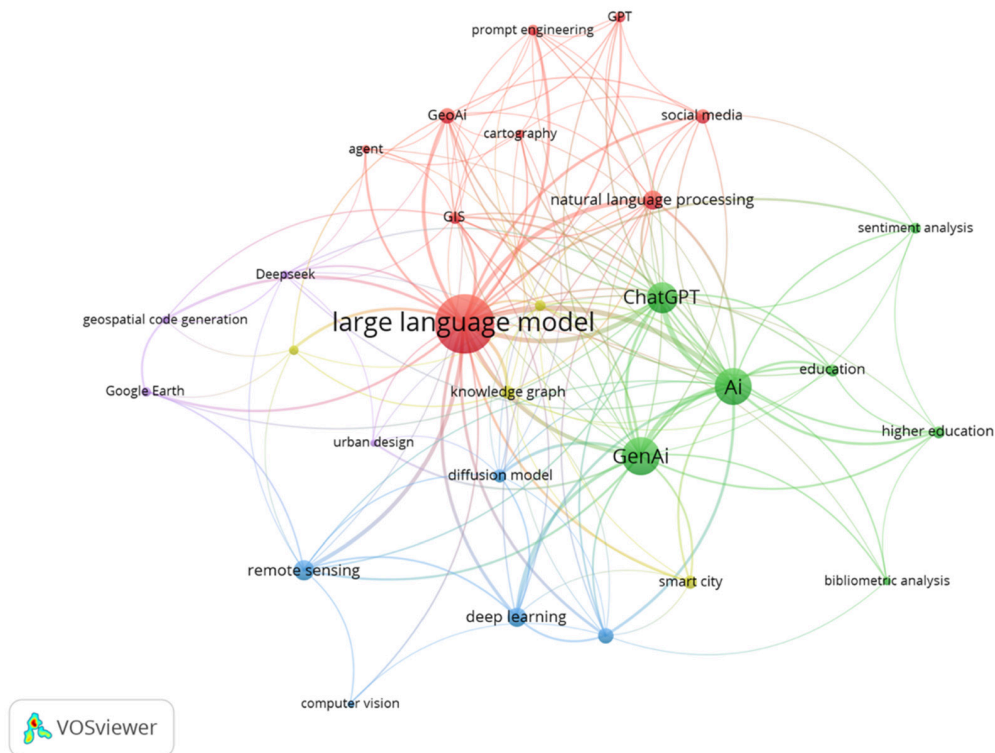
The red cluster, “LLM-Based GeoAI and GIS,” centers on LLM-oriented GeoAI and language-driven geographic workflows. Keywords such as “large language model,” “GPT,” “ChatGPT,” “GeoAI,” “GIS,” “cartography,” “natural language processing,” “prompt engineering,” and “agent” are included this cluster. This grouping reflects research focused on natural language interaction with geospatial data, automated cartographic design, and LLM-based spatial reasoning and task orchestration. The association between LLM-related terms and GIS concepts indicates that generative language models are being operationalized as interfaces, reasoning components, or agents within established geographic information infrastructures rather than as purely abstract language systems [3].

The green cluster, “GenAI in Scholarly Communication and Education,” emphasizes educational, analytical, and reflective uses of GenAI in geographic contexts. This cluster includes keywords such as “AI,” “GenAI,” “education,” “higher education,” and “social media.” Within geography, this cluster captures applications that engage with GenAI as a tool for analyzing spatially referenced narratives, public opinion, and scholarly communication, as well as for supporting teaching and learning in geographic and related fields [23].

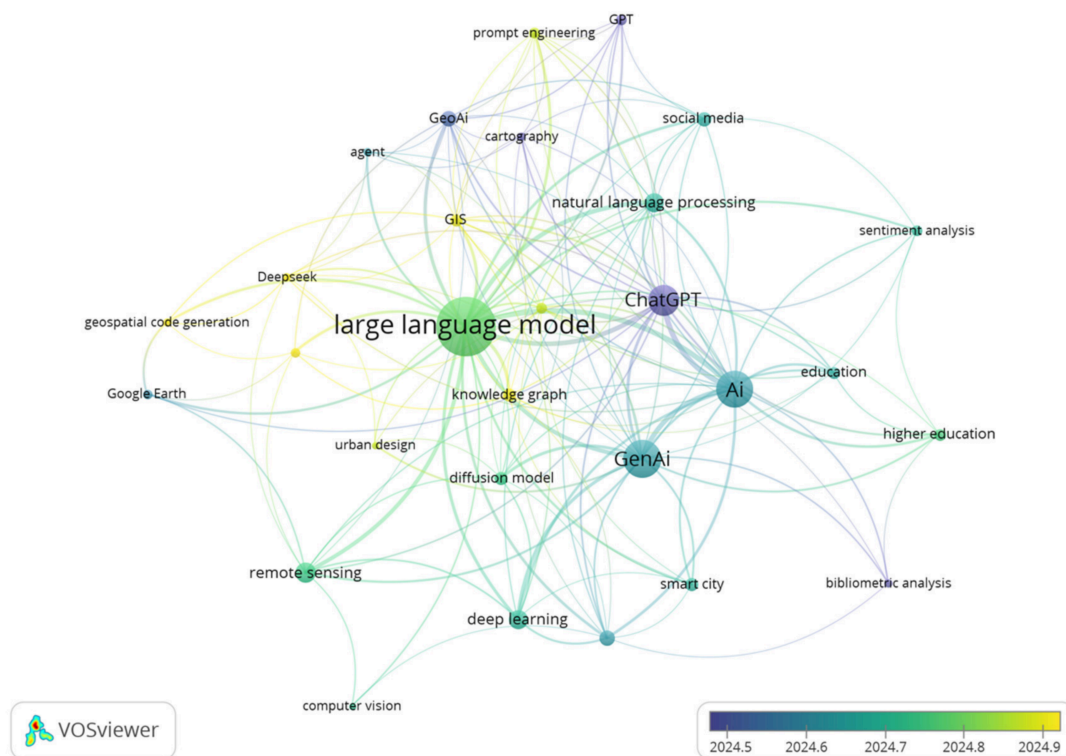
The blue cluster, “Machine Learning and Earth Observation Foundations,” is dominated by image-based and computational modeling keywords. Keywords including “computer vision,” “deep learning,” “diffusion model,” “machine learning,” and “remote sensing” define this group. The structure of this cluster indicates continuity between deep learning-based remote sensing research and newer generative approaches, particularly diffusion-based image generation and enhancement methods [8].

The yellow cluster, “Knowledge-Driven Urban Analytics,” encompasses keywords such as “knowledge graph,” “retrieval-augmented generation,” “smart city,” and “urban planning” are grouped together, indicating a thematic focus on integrating structured geographic knowledge with generative models to support urban analysis and planning tasks. These keywords suggest that GenAI is increasingly used in conjunction with external knowledge bases and retrieval mechanisms to enhance contextual awareness and decision support in complex urban systems [33].

The purple cluster, “Geospatial GenAI Tools and Platforms,” captures platform- and application-specific geospatial implementations. Keywords including “DeepSeek,” “geospatial code generation,” “Google Earth,” and “urban design” define this group. This cluster reflects experimentation with concrete platforms, tools, and generative coding systems that operationalize GenAI within practical geospatial environments.



(a)



(b)

Figure 4. Network map of keywords on GenAI and geography research: (a) co-occurrence network visualization showing the clustering structure of keywords (above); (b) overlay visualization showing the average occurrence time of keyword occurrences (below). (Note: In (a), colors represent the cluster membership assigned by VOSviewer (version 1.6.20) to denote groups of related keywords. In (b), colors represent the average occurrence time assigned by VOSviewer (version 1.6.20), as indicated by the color legend).

The overlay visualization based on average keyword occurrence reveals a clear temporal evolution in GenAI-related geographical research (Figure 4b). Overall, the results show a shift from early, model-centered and reflective inquiry toward more integrated, tool-oriented, and application-driven research. Keywords with earlier average occurrence, shown in purple or blue, include GPT, ChatGPT, and cartography, suggests that initial research interests were strongly influenced by the rapid public visibility of specific large language model families, particularly ChatGPT, which functioned both as a research object and as an accessible analytical tool. This pattern is consistent with earlier technological shifts in geography, where new digital tools are first explored through conceptual framing [11,32].

A transitional group of keywords, concentrated in green, marks the consolidation phase of the field. Terms such as large language model, GenAI, and AI indicate movement away from named systems toward broader model categories. At the same time, deep learning, machine learning, remote sensing, computer vision, and diffusion model reflect the integration of generative approaches into established computational and Earth observation traditions. The keywords such as natural language processing, social media, and sentiment analysis point to expanding use of textual and socio-spatial data, while smart city, education, and higher education indicate growing interest in applied and institutional contexts [4].

The most recently occurring keywords, highlighted in yellow, signal a further shift toward system-level integration and practical workflows. Terms such as prompt engineering, retrieval-augmented generation, knowledge graph, and geospatial code generation reflect increasing emphasis on tool-using pipelines that combine generative models with structured knowledge and executable spatial operations. The appearance of GIS, urban planning, and urban design suggests deeper embedding of GenAI within core geographical tools and professional practices, particularly in urban contexts [9].

4.4. Documents

The highly cited documents indicate that highly influential contributions span three main application loci (Table 5). A first locus concerns higher education and learning contexts, including academic integrity, pedagogical affordances, and user adoption. The single most-cited article addresses GenAI and the future of higher education through an academic integrity lens [44], while additional highly cited works address language teaching [45], responsible use of AI chatbots for teaching and learning [46], user adoption of ChatGPT using technology acceptance framing [47], and systematic review synthesis of ChatGPT in higher education [48]. These documents concentrate citations in education-oriented outlets and human–computer interaction venues, indicating that educational deployment and governance questions constitute a high-visibility strand within the corpus.

Table 5. Highly cited articles on GenAI and geography research.

Rank (nth)	Articles ¹	Title	Year	Journal	Citations
1	Yusuf et al. [44]	Generative AI and the future of higher education: A threat to academic integrity or reformation? Evidence from multicultural perspectives	2024	International Journal of Educational Technology in Higher Education	241

Table 5. Cont.

Rank (nth)	Articles ¹	Title	Year	Journal	Citations
2	Hu et al. [49]	Geo-knowledge-guided GPT models improve the extraction of location descriptions from disaster-related social media messages	2023	International Journal of Geographical Information Science	130
3	Haluza & Jungwirth [50]	Artificial intelligence and ten societal megatrends: An exploratory study using GPT-3	2023	Systems	127
4	Jiang et al. [51]	Generative urban design: A systematic review on problem formulation, design generation, and decision-making	2024	Progress in Planning	120
5	Zhang et al. [52]	EarthGPT: A universal multimodal large language model for multi-sensor image comprehension in remote sensing domain	2024	IEEE Transactions on Geoscience and Remote Sensing	120
6	Crompton et al. [45]	AI and English language teaching: Affordances and challenges	2024	British Journal of Educational Technology	111
7	Ma et al. [47]	Exploring user adoption of ChatGPT: A technology acceptance model perspective	2025	International Journal of Human-Computer Interaction	108
8	Li et al. [53]	Vision-language models in remote sensing: Current progress and future trends	2024	IEEE Geoscience and Remote Sensing Magazine	106
9	Li & Ning [54]	Autonomous GIS: The next-generation AI-powered GIS	2023	International Journal of Digital Earth	103
10	Liu et al. [55]	RSCAMA: Remote sensing image change captioning with state space model	2024	IEEE Geoscience and Remote Sensing Letters	102
11	Zhang et al. [26]	GeoGPT: An assistant for understanding and processing geospatial tasks	2024	International Journal of Applied Earth Observation and Geoinformation	89
12	Liu et al. [56]	A decoupling paradigm with prompt learning for remote sensing image change captioning	2023	IEEE Transactions on Geoscience and Remote Sensing	79
13	Zhang et al. [17]	TrafficGPT: Viewing, processing and interacting with traffic foundation models	2024	Transport Policy	77

Table 5. Cont.

Rank (nth)	Articles ¹	Title	Year	Journal	Citations
14	Jiang et al. [57]	Eplus-LLM: A large language model-based computing platform for automated building energy modeling	2024	Applied Energy	75
15	Baig & Yadegaridehkordi [48]	ChatGPT in the higher education: A systematic literature review and research challenges	2024	International Journal of Educational Research	72
16	Mai et al. [58]	On the opportunities and challenges of foundation models for GeoAI	2024	ACM Transactions on Spatial Algorithms and Systems	67
17	Zhu et al. [59]	A flood knowledge-constrained large language model interactable with GIS: Enhancing public risk perception of floods	2024	International Journal of Geographical Information Science	63
18	Bazi et al. [60]	RS-LLAVA: A large vision-language model for joint captioning and question answering in remote sensing imagery	2024	Remote Sensing	62
19	Tao & Xu [61]	Mapping with ChatGPT	2023	ISPRS International Journal of Geo-Information	61
20	Chauncey & McKenna [46]	A framework and exemplars for ethical and responsible use of AI chatbot technology to support teaching and learning	2023	Computers and Education: Artificial Intelligence	58
21	Zhang et al. [27]	BB-GeoGPT: A framework for learning a large language model for geographic information science	2024	Information Processing and Management	57
22	Liu et al. [62]	Change-agent: Toward interactive comprehensive remote sensing change interpretation and analysis	2024	IEEE Transactions on Geoscience and Remote Sensing	56
23	Liao et al. [63]	GPT-4 enhanced multimodal grounding for autonomous driving: Leveraging cross-modal attention with large language models	2024	Communications in Transportation Research	55
24	Yang et al. [64]	Bootstrapping interactive image-text alignment for remote sensing image captioning	2024	IEEE Transactions on Geoscience and Remote Sensing	53

Table 5. Cont.

Rank (nth)	Articles ¹	Title	Year	Journal	Citations
25	Zou et al. [65]	Deep learning for cross-domain data fusion in urban computing: Taxonomy, advances, and outlook	2025	Information Fusion	51

¹ Only the articles that have at least 50 citations are shown.

A second locus centers on remote sensing and Earth observation, with influential work focused on multimodal understanding, captioning, and change interpretation. Highly cited contributions include a multimodal LLM for remote sensing image comprehension [17], reviews of vision-language models in remote sensing [53], remote sensing image change captioning and related prompt-learning or state-space approaches [55,56,62], and large vision-language models for joint captioning and question answering in remote sensing imagery [60]. Influence in this locus is concentrated in remote sensing and IEEE geoscience outlets, consistent with a technically oriented citation economy that privileges scalable benchmarks, generalizable architectures, and reproducible pipelines.

A third locus reflects GIScience and geospatial task support, where influential documents develop or anticipate LLM-based assistants and AI-powered GIS systems. Highly cited documents include an assistant for understanding and processing geospatial tasks [26], a framework for learning an LLM for geographic information science [27], autonomous or next-generation AI-powered GIS concepts [54], and domain-specific foundation-model assistants in adjacent applied contexts, such as traffic foundation models [17] and LLM-based platforms for automated building energy modeling [51]. Several highly cited documents in this locus explicitly integrate external knowledge resources with geospatial workflows, including geo-knowledge-guided GPT for extracting location descriptions from disaster-related social media [49] and an LLM interactable with GIS to support flood risk perception [59]. These documents concentrate citations in GIScience and applied Earth observation outlets, indicating that influence is strongly tied to tool-building and task operationalization.

To explore the intellectual bases of the field, a co-citation analysis was conducted on 46 references with a minimum co-citation frequency of five, yielding nine clusters (Figure 5). In the resulting network visualization, four overlapping clusters (red, brown, orange, and purple) occupy the central region, while five others (green, blue, yellow, turquoise, and pink) extend outward from this core, indicating more specialized or peripheral citation relationships. The thematic structure of the network is not a simple juxtaposition of technical development and normative discussion, but reflects an ongoing effort to render GenAI usable, credible, and accountable in geographic knowledge production. Across the clusters, research repeatedly emphasizes the need to anchor generative models in reliable measurement systems, to situate them within shared disciplinary narratives and mapping practices, and to frame their use through explicit consideration of risks, governance, and educational implications.

The red cluster encompasses documents in geodesy, atmospheric correction, and GNSS-related modeling that support spatial positioning and tropospheric delay estimation, alongside early machine learning approaches applied to environmental and geospatial modeling [66–68]. The purple cluster links large-scale mapping methods with foundational natural language processing architectures and survey papers that are frequently cited when positioning the field and describing model families used in geographic applications [69,70]. The orange cluster groups critical and societal discussions of GenAI, including risks, harms,

and educational implications, together with applied analyses of how generative tools shape education and public-facing communication contexts [16,71]. The brown cluster is organized around transformer architectures and foundation-model discourse, including the attention mechanism, influential arguments about foundation-model capabilities, and domain adaptations for geographic language tasks such as place-name recognition and extraction [72,73]. These four overlapping clusters portray a field that is consolidating around the translation of rapidly advancing general-purpose AI into a domain that is highly method-dependent, infrastructure-bound, and socially consequential.

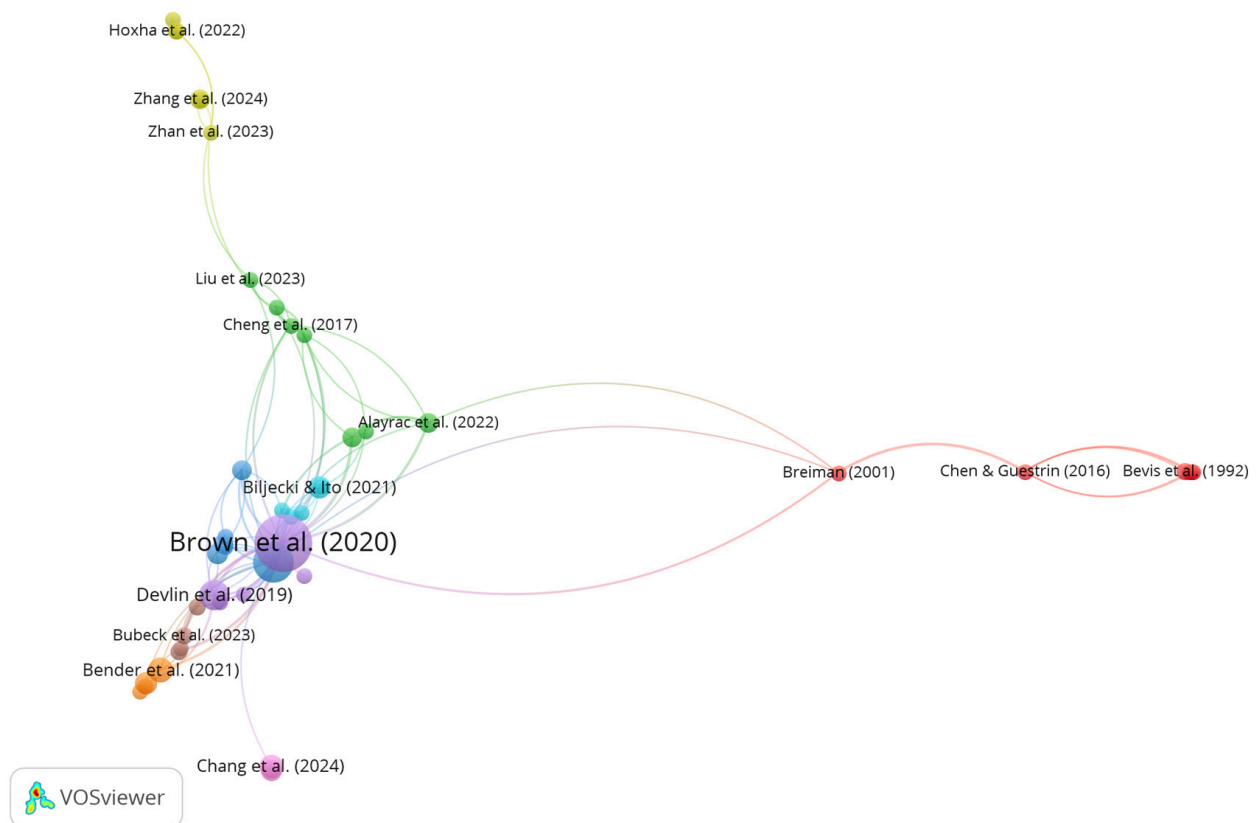


Figure 5. Co-citation clusters of documents on GenAI and geography research. (Note: colors represent the cluster membership assigned by VOSviewer (version 1.6.20) to denote groups of related documents).

Extending from this core are five clusters representing more specialized applications and methodological orientations. The green cluster centers on semantic scene understanding that combines visual representation learning, benchmark-driven evaluation, and instruction-oriented vision–language modeling for human-interpretable image analysis [74–76]. The blue cluster encompasses core foundation-model families and open model reports, including GPT-4 technical documentation, LLaMA-family releases, and representation-learning resources widely used in multimodal alignment [77–79]. The yellow cluster is dominated by remote sensing vision-language and multimodal modeling studies, including approaches to captioning, grounding, change interpretation, and multimodal remote sensing assistants [26,80,81]. The turquoise cluster links machine learning and topic-modeling foundations in applied geographic contexts [82]. Finally, the pink cluster encompasses qualitative thematic analysis and systematic evaluation of large language models [83].

5. Discussion

5.1. Temporal and Spatial Development of the Field

The results reveal an exceptionally compressed temporal trajectory in the development of GenAI-related geographical research. Initially, only 11 articles on GenAI-related topics in 2022 was published in 2022. The small number of publications reflects the nascent stage of generative AI adoption in geography, where AI applications were still largely dominated by traditional machine learning and deep learning approaches, such as classification, prediction, and pattern recognition in remote sensing and spatial analysis, rather than generative models [8]. The number of publications increased modestly to 45 articles in 2023, marking the beginning of more systematic engagement with GenAI in geographical research. This increase corresponds with the broader academic diffusion of large language models and generative foundation models following their public release and rapid uptake across disciplines [69,77]. During this phase, geographical studies began experimenting with GenAI for tasks such as text-based spatial analysis, geographic knowledge extraction, map generation, and scenario simulation.

A pronounced acceleration is observed in 2024, with 204 articles published, representing a nearly fivefold increase compared to 2023. This sharp rise suggests a transition from exploratory adoption to more established and diversified applications of GenAI within geography [35]. The upward trend continues into 2025, with 631 articles published within the year covered by the dataset. This substantial increase indicates that GenAI has rapidly become a mainstream research topic in geography, attracting sustained scholarly attention across multiple subfields. The strong publication output in 2025 highlights the growing recognition of GenAI as both a powerful analytical tool and a subject of theoretical and ethical inquiry in geographical research. The rapid increase in publication output was also accompanied by shifts in thematic emphasis which will be subsequently discussed in Section 5.3.

The spatial distribution of publications indicates strong concentration, with China (40.9%) and the United States (22.6%) jointly accounting for 63.4% of the corpus. This level of concentration is consistent with recent GeoAI syntheses that describe uneven capacity in geospatial computing, data infrastructure, and model development, with leadership concentrated in a small number of national innovation systems [4]. The institution-level results add a complementary view of how national productivity can be organized. The most productive institution list contains many entries from a single country and includes large umbrella organizations, indicating that a substantial share of national output can be concentrated into a set of high-throughput hubs that publish at scale. At the same time, a large national share combined with few top-ranked institutions suggests that publication output is spread across many universities and research groups rather than concentrated in a small number of high-output hubs, a pattern also observed in recent bibliometric analyses of GeoAI and geospatial data science that distinguish between hub-based and distributed modes of knowledge production [16]. This configuration implies that national dominance can arise through at least two institutional pathways, concentrated hub production and broadly distributed institutional participation, and that these pathways can coexist within the same fast-expanding field.

5.2. Disciplinary Composition of GenAI-Related Geographical Research

The disciplinary composition of the corpus underscores the hybrid positioning of GenAI within geography. The strong representation of Computer Science, Engineering, and Earth and Planetary Sciences reflects the technical foundations required for developing and adapting generative models to spatial data, a pattern consistent with recent GeoAI syntheses that situate model development, multimodal learning, and scalable computing

as key capacity constraints in geospatial research [11,41]. A distinguishing feature in this corpus is the comparable prominence of Social Sciences, suggesting that generative models are being taken up not only as analytical tools but also as objects of inquiry in urban and planning contexts where governance and practice questions are salient [9].

Journal-level evidence supports this hybrid composition. The leading outlets are dominated by remote sensing, geoscience, and GIScience journals, which indicates that technically oriented publication venues remain primary channels for GenAI-related geographical research. At the same time, the presence of urban studies, planning, sustainability, and humanities-oriented journals indicates broader disciplinary engagement than is typically emphasized in GeoAI reviews, which often foreground remote sensing, mapping, and spatial analytics applications [10,41]. The bibliographic coupling structure is consistent with differentiation by outlet type, with clusters corresponding to remote sensing and Earth observation, GIScience and spatial information, and urban and planning journals. The existence of linkages among these clusters suggests that GenAI functions as a connective methodological layer that supports shared citation bases and cross-venue exchange, particularly through language-based and multimodal techniques that can be adapted across technical and social-science problems.

5.3. Research Themes and Trends

The synthesis of keyword frequency, thematic clustering, and average occurrence time indicates that GenAI-related geographical research has undergone rapid thematic evolution within a short time span [11]. This progression is visible as shifts in the vocabulary that dominates different parts of the keyword network, and as changes in which thematic groupings attract the most attention. While some themes are associated with earlier interests in emerging GenAI platforms and conceptual exploration, others reflect more recent attention to domain-specific applications, workflow integration, and operational implementation. The temporal patterns observed in the overlay visualization therefore suggest an increasingly diversified research landscape rather than a single uniform developmental trajectory.

The LLM-based GeoAI and GIS theme functions as a central articulation point because it links general model terms with geographic representations and operational GIS language [34,54]. Its vocabulary shifts from earlier platform references and cartographic framing (GPT, ChatGPT, cartography) toward more recent workflow-oriented terms that support operational use (prompt engineering, retrieval-augmented generation, GIS), indicating that attention moved from experimenting with model capabilities and representational implications toward configuring LLMs as components in GIS-oriented toolchains [3,11]. This pattern suggests a gradual shift in emphasis from platform-centered exploration toward the practical integration of LLMs within geospatial workflows.

The theme of GenAI in scholarly communication and education concentrates on applied analytical contexts and institutional settings where adoption, practice, and evaluation are salient [44]. Its keyword profile is dominated by transitional terms (education, higher education, social media, sentiment analysis, natural language processing) that indicate integration into common analytical pipelines and learning environments after initial platform uptake [4]. This theme highlights that a significant share of geographic GenAI work addresses human-facing settings where use practices and evaluation norms become part of the research agenda [84]. The continued prominence of these keywords suggests that questions of adoption, evaluation, and responsible use remain persistent concerns within the broader development of the field.

The theme of machine learning and earth observation foundations is organized around established image-centered methods and their generative extensions [10]. Keywords such as remote sensing, computer vision, deep learning, machine learning, and diffusion model

point to a line of work that adapts generative and multimodal methods to Earth observation tasks [8,26]. The overlay visualization associates much of this vocabulary with relatively later developments in the network, suggesting growing interest in extending generative approaches beyond language-centered applications into image-intensive and data-rich geographical domains.

The knowledge-driven urban analytics theme links urban domain terms with system components that support structured reasoning [33]. Smart city appears as a transitional anchor, while more recent terms such as urban planning, urban design, and knowledge graph indicate increasing emphasis on coupling generative models with structured knowledge resources in decision-support contexts [33]. The appearance of these more recent keywords suggests increasing attention to specialized planning and governance applications that require the integration of generative models with explicit knowledge structures. This theme indicates movement toward hybrid architectures that combine generative outputs with explicit representations used in urban and planning applications [9].

The geospatial GenAI tools and platforms theme concentrate on implementation, deployment, and interaction with geospatial software environments [11]. Recent keywords such as geospatial code generation and retrieval-augmented generation, together with platform signals and GIS terms, indicate a shift toward tool-building and code-mediated operation on geospatial data [41]. The temporal profile of this grouping suggests that operationalization has become more salient as the field matures [11]. The growing prominence of these keywords indicates increasing interest in workflow automation, executable geospatial operations, and practical deployment within geospatial environments.

Across these themes, a small set of general model keywords (LLM, GenAI, AI) operate as cross-cutting connectors rather than theme identifiers [16]. Their central placement in the network reflects how LLMs provide common reference points that support multiple application areas, while thematic differentiation is carried by more domain- and workflow-specific keywords [11]. This interpretation aligns with recent geospatial GenAI syntheses that describe foundation models as enabling infrastructure whose impact is expressed through downstream workflows and domain adaptations [41].

5.4. Seminal Works and Intellectual Foundations

The highly cited documents highlight where GenAI-related geographical research has produced widely referenced contributions. Influence concentrates in education, remote sensing, and GIScience, indicating that high-impact work emerges where generative systems intersect with large user communities and immediate operational demands. In education, the most cited contributions engage with academic integrity, responsible use, and adoption in higher education, and they resonate with broader post-2022 debates that have been rapidly institutionalized through journal guidance and policy discussion [4,16]. In remote sensing and Earth observation, highly cited work prioritizes multimodal vision-language models, change interpretation, and image understanding, reflecting a shift toward interactive and generative capabilities for geospatial imagery and spatiotemporal change contexts [55,56,60,62]. In GIScience, highly cited contributions emphasize assistants, autonomous or semi-autonomous GIS systems, and domain-specific foundation models, indicating movement toward workflow-level integration and human-in-the-loop systems [17,26,27].

The co-cited reference clusters represent the intellectual base that is repeatedly mobilized across the corpus, and they convey a different signal from the highly cited documents, as co-citation patterns capture shared theoretical, methodological, and technical foundations rather than visibility or influence measured through citation counts alone. Core clusters in the co-citation network are anchored in foundational contributions that predate

the emergence of GenAI in geography. These include early geodetic and atmospheric correction studies essential for spatial positioning and measurement [66,67], as well as seminal machine learning and natural language processing architectures such as transformers and large pretrained language models [16,69,70,72]. The presence of these works highlights the extent to which GenAI-related geographical research is built upon methodological infrastructures developed outside the discipline.

Equally notable are the specialized applications and methodological orientations extended from foundational contributions, including evaluation and benchmarking resources [74–76], LLM technical reports [77–79] and evaluation [83], and domain-specific multimodal modeling [52,80,81]. This configuration implies that a shared set of LLM references provides connective intellectual scaffolding across geographic subfields, while specialized studies supply targeted resources for validation, interpretation, and governance.

5.5. Emerging Research Gaps and Future Directions

The results and preceding discussion reveal several research gaps that point to important future directions for GenAI-related geographical research. First, despite the rapid growth of workflow-oriented studies, there remains a relative lack of systematic evaluation frameworks for assessing the reliability, reproducibility, and geographic validity of generative outputs. Much of the recent work on prompt engineering, retrieval-augmented generation, and geospatial code generation focuses on functional demonstrations rather than on comparative benchmarking or error characterization across spatial contexts. Recent reviews of geospatial GenAI similarly note that evaluation practices lag behind methodological innovation, particularly with respect to spatial reasoning, uncertainty propagation, and bias in geographically referenced outputs [11,41]. Addressing this gap will require the development of domain-specific benchmarks and standardized evaluation protocols tailored to geographic tasks.

Second, the thematic clustering highlights growing interest in knowledge-driven urban analytics and decision-support applications, yet empirical evidence on real-world adoption and institutional integration remains limited. While keywords such as urban planning, urban design, and knowledge graph signal an emerging research direction, most studies remain at the prototype or conceptual level. Future research could examine how generative systems are embedded in planning workflows, governance processes, and participatory settings, as well as how their outputs interact with regulatory frameworks and professional norms. These questions align with broader calls to examine the socio-technical implications of GenAI beyond technical performance alone [85].

Third, the prominence of general model-family keywords across themes suggests heavy reliance on a small number of foundation models and platforms. This concentration raises questions about model dependency, transparency, and accessibility in geographic research. In particular, this reliance is closely associated with the dominance of proprietary models, which may limit transparency and reduce user control over model behavior. In this context, open-source LLMs can provide greater flexibility for customization, local deployment, and integration with domain-specific geospatial data and tools, which are often required in geographic applications involving sensitive or region-specific information. Compared with proprietary systems, these models may also enhance transparency and reproducibility by allowing researchers to inspect model structures and adapt them to specific spatial contexts. However, despite these advantages, their role in geographic workflows remains underexplored in the current literature. Recent discussions in GeoAI and foundation model research emphasize the need for diversification and critical examination of model assumptions, particularly in spatially heterogeneous and data-scarce contexts [86]. Future

studies could explore the implications of proprietary versus open-source generative models, as well as the transferability of results across model architectures and training regimes.

Fourth, while the study notes that GenAI is increasingly discussed in relation to governance and responsible use, keywords associated with ethics, bias, or geospatial justice are not prominent in the keyword network or frequency analysis. This pattern suggests that current GenAI-related geographical research remains largely oriented toward instrumental and application-driven uses, with comparatively limited emphasis on critical and normative reflection [5]. Future research could further engage with ethical, social, and justice-related dimensions of GenAI in geographic contexts.

5.6. Theoretical and Practical Implications

From a theoretical perspective, the findings suggest that GenAI may be reshaping geographical research not by introducing entirely new thematic domains, but by reconfiguring how existing concepts, methods, and applications are connected. The central role of large language models as connective infrastructure is consistent with a shift toward more integrative and workflow-oriented forms of geographic knowledge production. This observation extends existing GeoAI scholarship by highlighting the importance of interaction, orchestration, and system design, rather than algorithmic novelty alone, as key drivers of conceptual change [11,21].

Practically, the results indicate growing opportunities for deploying GenAI within operational geographic contexts, particularly in GIS workflows, urban planning, and education. The emergence of tool-oriented themes suggests that generative models are increasingly positioned as interfaces between users, data, and analytical systems. However, this shift also underscores the need for capacity building, ethical guidance, and governance mechanisms to support responsible use [87]. Recent studies on GenAI in geographic and environmental education highlight both the pedagogical potential and the risks associated with uncritical adoption, reinforcing the importance of integrating technical innovation with institutional and normative considerations [4].

5.7. Limitations

The findings of this study should be interpreted in light of several limitations, each of which also points to avenues for methodological improvement in future research. First, the bibliometric analysis relies on publications indexed in a single database, which may under-represent relevant studies published in non-English journals, regional outlets, conference proceedings, or practitioner-oriented venues. Future research could address this limitation by integrating multiple databases or complementary data sources, thereby providing a more comprehensive representation of GenAI-related geographical research.

Second, the search strategy emphasizes general GenAI and LLM-related terminology. Therefore, articles referencing only model-specific names (e.g., diffusion and multimodal models, as well as specific open-source or proprietary model families) without broader GenAI or LLM framing may fall outside the query. Future research could address this limitation by expanding the keyword design to include a broader range of generative model categories.

Third, the analysis is based on keyword co-occurrence and co-citation patterns, which depend on author-supplied keywords and indexing practices. As a result, some conceptual nuances or emerging research ideas may not be fully captured, particularly in a rapidly evolving field where terminology changes quickly. Bibliometric mapping is therefore complementary to, not a substitute for, close reading and qualitative synthesis. The thematic labels assigned to clusters reflect the authors' interpretation of keyword groupings and should be treated as heuristic rather than definitive. Future studies could combine the

structural map produced here with systematic qualitative coding of representative articles within each cluster, thereby testing and enriching the thematic interpretations derived from network analysis alone.

Fourth, the temporal scope of the study is restricted to post-2022 publications. While this focus is appropriate for examining the emergence of GenAI, it limits the ability to trace longer-term continuities and ruptures with earlier strands of GeoAI and artificial intelligence research. Future work could extend the temporal window or conduct comparative analyses between pre- and post-GenAI periods to better contextualize recent developments.

Finally, co-occurrence and co-citation analyses reveal patterns of association rather than causal relationships. The structural and developmental interpretations presented in this Discussion should therefore be understood as indicative rather than explanatory. Future research could complement bibliometric approaches with empirical studies, case analyses, or longitudinal investigations to examine causal mechanisms underlying the observed research dynamics.

6. Conclusions

This study provides a comprehensive bibliometric examination of GenAI-related geographical research published since 2022, capturing patterns associated with the rapid emergence and consolidation of this field in the wake of advances in large language models and generative systems. By integrating performance analysis with scientific mapping techniques, the study delineates publication trends, disciplinary composition, thematic structures, and intellectual foundations that characterize the current research landscape.

The findings indicate that GenAI-related geographical research has expanded at an exceptional pace and exhibits pronounced spatial concentration, with national and institutional patterns reflecting different modes of knowledge production. Disciplinary analysis highlights the hybrid nature of the field, positioned at the intersection of geography, GI-Science, remote sensing, computer science, and social science-oriented application domains. Keyword-based analyses suggest a thematic structure organized around cohesive research themes, accompanied by clear shifts in research emphasis from early exploratory framing to methodological consolidation and, more recently, toward workflow-level integration and operational deployment. Document-level analyses indicate that highly cited contributions and co-cited intellectual bases convey complementary insights into influence and foundational knowledge, underscoring the layered structure of the field's development.

Taken together, the results and discussion suggest that GenAI may be reshaping geographical research primarily through reconfiguration rather than thematic replacement. Generative models appear to function as connective infrastructure that links established methods, application domains, and emerging workflows, potentially accelerating integration across previously distinct research strands. At the same time, the analysis identifies important gaps related to evaluation practices, institutional embedding, and model dependency, suggesting that future progress will depend not only on technical innovation but also on methodological rigor, governance, and reflective engagement with the socio-technical dimensions of GenAI.

By systematically mapping the development, structure, and trends of GenAI-related geographical research, this study contributes a systematic and integrative empirical foundation that extends beyond existing narrative and application-focused reviews, thus providing a clearer understanding of how generative technologies are being incorporated into geographic scholarship. The results provide a reference point for researchers, educators, and practitioners seeking to situate their work within this rapidly evolving field, and they offer guidance for future research aimed at advancing both the theoretical and practical integration of GenAI in geography.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
GAN	Generative Adversarial Network
GenAI	Generative Artificial Intelligence
GeoAI	Geospatial Artificial Intelligence
GIS	Geographic Information Science
GIS	Geographic Information System
GPT	Generative Pre-trained Transformer
LLM	Large-Scale Language Model

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