

Research on geodiversity in Brazil: a bibliometric analysis

Investigación sobre geodiversidad en Brasil: un análisis bibliométrico

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ABSTRACT

Geodiversity, which encompasses the variety of abiotic components (geological, geomorphological, pedological, hydrological, and climatic), is crucial for ecosystem health and biodiversity. Brazil, with its vast and complex geological framework, has seen a notable increase in geodiversity research, yielding significant implications for environmental management, conservation strategies, and biodiversity studies. This paper reviews the current state of research on this topic in Brazil, highlighting key findings, the challenges of geoconservation, and advancements in research directions within the context of the country's geodiversity. This bibliometric analysis, which examines 393 documents indexed in the Scopus and Web of Science (WoS) databases covering the period from 2003 to 2024, provides a comprehensive overview of the scientific production on geodiversity in Brazil, indicating trends, key contributors, and thematic focuses. The study underscores the growing importance of geodiversity, particularly in the context of geoconservation and biodiversity preservation.

Keywords: state of art, geodiversity in Brazil, bibliometric, geodiversity.

RESUMEN

La geodiversidad, entendida como la variedad de los componentes abióticos (geológicos, geomorfológicos, pedológicos, hidrológicos y climáticos), es crucial para la salud de los ecosistemas y la biodiversidad. Brasil, poseedor de un vasto y rico patrimonio geológico y biológico, ha experimentado un notable aumento en la investigación sobre geodiversidad, lo cual tiene importantes implicaciones para la gestión ambiental, las estrategias de conservación y los estudios de biodiversidad. Este artículo revisa el estado actual de la investigación sobre este tema en Brasil, destacando los hallazgos clave, los desafíos para la geoconservación y los avances en las líneas de investigación en el contexto de la geodiversidad nacional. Este análisis bibliométrico, que examina 393 documentos indexados en las bases de datos Scopus y Web of Science (WoS) durante el periodo 2003-2024, ofrece una visión general exhaustiva de la producción científica en geodiversidad en Brasil, identificando tendencias, contribuyentes clave y enfoques temáticos. El estudio subraya la creciente importancia de la geodiversidad, particularmente en el contexto de la geoconservación y la preservación de la biodiversidad.

Palabras clave: estado del arte, geodiversidad en Brasil, bibliometría, geodiversidad.

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1. Introduction

The concept of geodiversity has gained recognition lately, primarily due to its intrinsic links with biodiversity and ecosystem services, considering that geodiversity provides the foundation for understanding ecological processes and biodiversity patterns. It also plays a crucial role in maintaining ecological balance and supporting biodiversity.

Numerous concepts of geodiversity have been proposed since research on the subject first emerged in the 1990s. Recently, a paper signed by 20 authors (Maliniemi *et al.*, 2024), including the most prominent researchers on geodiversity in the world, argued against what they consider a considerable number of concepts on geodiversity. The authors argued that the large number of existing concepts could hinder the effective use of geodiversity in biodiversity research and advocated for the exclusive use of Gray's (2013) definition. According to Gray (2013), geodiversity refers to the natural variety of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil, and hydrological elements found on Earth's surface. Nevertheless, this definition is incomplete because it does not include climate.

Consequently, the expanded concept proposed by Claudino-Sales (2021a) was adopted, encompassing the full abiotic dimension of a region—the variety of geological, geomorphological, pedological, hydrological, and climatic characteristics—and was used as a basis to present the state of the art in geodiversity research in Brazil.

Brazil, a country renowned for its natural richness, complex geological frameworks, varied landscapes and soils, rich hydrography, and diverse climatic elements, presents unique opportunities for studying geodiversity. For these reasons, research on geodiversity has shown prominence in recent years in Brazil. Most of the studies have classically explored geological and geomorphological features and mapping, but more recently, research products are opening

the range of possibilities to analyze hydrological and pedological diversity as well, while climatic geodiversity remains theoretical. Here, it is considered that climate is an important element of the abiotic environment, in such a way that it cannot be considered just as a process, as Gray (2013) suggests, but rather a condition to analyze geodiversity in a region.

The collective contributions of this research indicate that understanding geodiversity in the country is vital not only for ecological health but also for sustainable development and resource management. Brazil's geodiversity offers a wealth of research opportunities that are critical for understanding the complexity of its abiotic formations and processes. From economic resource exploration to geomorphological studies and the assessment of natural hazards, the Brazilian landscape is rich with insights that impact various sectors, including environmental policy, urban planning, and natural resource management. As such, ongoing research in this field is vital for advancing knowledge and promoting sustainable practices in one of the world's most environmentally diverse countries.

In this context, systematic reviews are important for understanding the theoretical and conceptual development of a field by synthesizing scientific output and identifying existing gaps in the literature (Ellegaard and Wallin, 2015; Donthu *et al.*, 2021). Bibliometric analyses of the terms “geodiversity,” “geoconservation,” “geotourism,” and “geopark” highlight Brazil as one of the five countries with the highest number of publications on these topics (Ibáñez *et al.*, 2019; Herrera-Franco *et al.*, 2022). This positions the country as an emerging focus in the field, driven by efforts to identify, document, and preserve natural resources and geological and cultural heritage—exemplified by the designation of territories such as geoparks for the United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage sites (Piranha *et al.*, 2011; UNESCO, 2025).

It is considered that sciences in general are practiced more by men than by women, which is repeated in Earth Sciences in general. However,

in the field of geodiversity and geoheritage in Brazilian production, studies by women seem to have a relevant role, being a question of this research to investigate what the quantitative participation of women in the most qualified production is.

Considering the above, the objective of the present research was to carry out a quantitative and qualitative analysis of Brazilian production in the fields of geodiversity, considering articles produced in journals with internationally disseminated indexes. The objective was also to quantitatively consider the female participation among the most relevant researchers in the country in these fields.

2. Methodology

The research was conducted by collecting data from the Scopus and Web of Science (WoS) indexers, accessed through the Coordination for the Improvement of Higher Education Personnel (CAPES), with access from the Federated Academic Community (CAFe). The search terms were “geodiversity” or “geodiversidade” (in Portuguese) or “geoheritage” or “geomorphodiversity” or “hydrodiversity” or “pedodiversity”. The searches were conducted in the Scopus portal using the fields “Article Title, Abstract, and Keywords” and in the WoS portal using the field “Topic”, which includes “Title, Abstract, Author’s Keywords, and Keywords Plus”. The scope of the research was limited to studies conducted in Brazil until the year 2024.

A total of 527 documents were collected from the Scopus and WoS databases. These were subsequently merged, and 127 duplicate records were removed. Then, the articles selected for the systematic review were screened based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Figure 1; Page *et al.*, 2021). After screening, seven documents were manually excluded for not aligning with the research theme, resulting in 393

articles analyzed in this study. The data analysis was conducted in the R programming environment, version 4.4.2 (R Core Team, 2024), and RStudio software, version 2024.12.1+563 (Posit Team, 2025). The bibliometrix package (Aria and Cuccurullo, 2017) was used for processing and analyzing the data.

After the quantitative analysis to identify the Annual Scientific Production, Most Productive Authors, Top manuscripts per citations, Most Relevant Sources, Most Relevant Keywords and Authors with the highest number of publications. In the analysis of institutional affiliation reported by the researchers, a loss of data was noted during the unification of the WoS and Scopus databases; therefore, it was decided to use the primary data from each database. A qualitative analysis and data refinement were performed using Google Sheets. Finally, the data were represented graphically using Infogram (Prezi Inc., 2025).

3. Results of quantitative data from the WoS and Scopus portal

A total of 393 articles were produced by Brazilian researchers and published in 121 journals. These publications are predominantly co-authored, with an average of 4.06 authors per document and 1,597 author appearances overall, including 13 single-authored papers. 18.32% of the articles involve international collaboration. The analysis covers the period from 2003 to 2024. Production has been increasing in recent years, with more than 70% of articles published between 2019 and 2024 (Figure 2). The year with the most articles published was 2022, with 61 articles, probably due to the availability of time generated by the COVID-19 lockdown, which led to the release of research that had been delayed or not published. After this year, production decreased to 47 articles in 2023 and increased to 52 articles in 2024. The words that were most repeated in the keywords of the papers were geodiversity, geoconservation, geoheritage, geotourism, geosites, geological heritage, inventory, Brazil, geoparks, ecosystem

services, and landscape (Figure 3). The most cited articles are presented in Table 1.

The most relevant affiliations of the authors are shown below (Figure 4). These institutions, primarily universities, stand out as the main hubs of scientific production in Brazil. Public universities play a central role in the development of research and the advancement of knowledge in the country.

Their strong presence among the most productive affiliations highlights their strategic importance in fostering academic output, training researchers, and consolidating geodiversity studies.

To complete the data, the journal *Geoheritage* ranks first, with 64 articles. Next come the Brazilian journals, highlighting both the relevance of national production and the wide dissemination of these works (Figure 5), since they are indexed in the WoS and Scopus databases. *Geoheritage* has an Impact Factor (IF) of 2.3 in WoS and a CiteScore of 5.1 in Scopus, while the *Anuário do Instituto de Geociências*, the second highest-ranked journal in number of articles, has a CiteScore of 0.7 in Scopus.

4. Women's participation in productions on geodiversity and geoconservation

Data was selected from the Most Productive Authors, considering those with at least two indexed publications during the period. In total, 158 authors were identified—107 men and 51 women—corresponding to a ratio of approximately two men for every woman with more than two publications. This result reflects a pattern observed in the Exact and Earth Sciences in Brazil. Official data indicate that, in 2023, only 35% of postgraduate scholarship holders in these fields were women, maintaining a ratio of nearly two men for every woman.

This reality is a fact. Confirming this assumption, the General Coordinator for the Popularization of Science and Technology of the Ministry of Science, Technology, and Innovation (MCTCI) of Brazil, Luana Bonone, said that the gender disparity by areas of knowledge reflects the traditional sexual division of labor. “In the exact and earth sciences, 35% of scholarship holders are women; in engineering and computing, they are 33.6% of scholarship

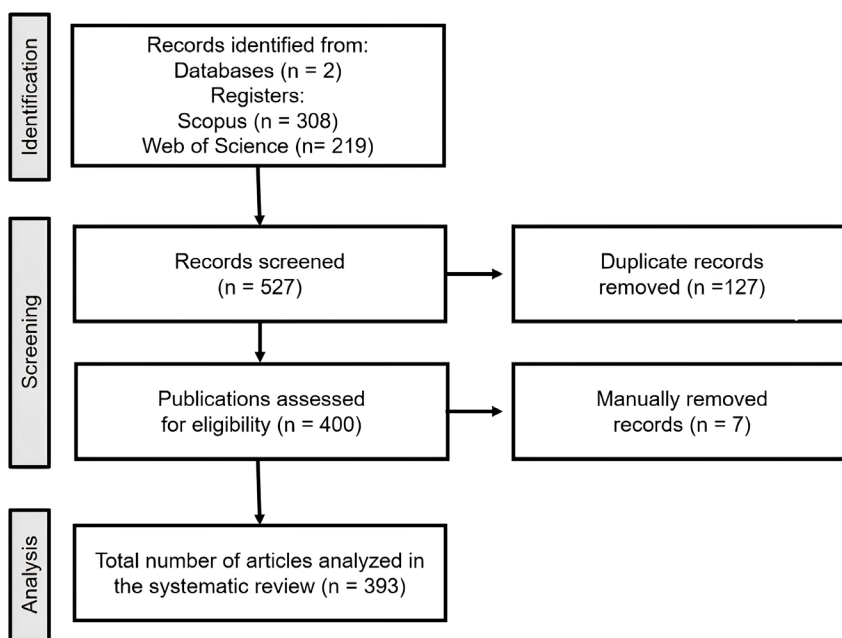


Figure 1 Flow diagram for systematic reviews, adapted from PRISMA 2020 (Page *et al.*, 2021).

holders—that is, only 1/3, while in other areas, such as linguistics, literature, arts, and health areas, 66% of scholarship holders are women, a percentage closer to the female participation in undergraduate studies”, she pointed out (Agência Câmara de Notícias, 2023).

However, when considering the 10 most significant authors, there are 5 men and 4 women. Figure 6 marks female authors with (F), and among all the researchers, Kátia Leite Mansur (38) and Maria da Glória Motta Garcia (32) were the ones who published the most in the period, followed by researchers Marcos Antonio Leite do Nascimento (31), Matheus Lisboa Nobre da Silva (17), Ursula de Azevedo Ruchkys (12), Ismar de Souza Carvalho (12), Marco Túlio Mendonça Diniz (9), and Thaís de Oliveira Guimarães (9).

The 10 most significant authors participated in the publication of 182 papers in total, with women authors in 91 of these articles and men authors in 91 articles. The large production of authors Kátia Mansur (38), Maria da Glória Garcia (32), Ursula Ruchkys (12), and Thais Guimarães (9) is decisive in the quantity and quality of Brazilian production in the areas of geodiversity and geoconservation.

5. Research on geodiversity in Brazil: State of the art

The study of geodiversity in Brazil started in the late 20th century. In 1999, a paper titled “A geodiversidade e o uso dos recursos minerais da Amazônia” (The geodiversity and the use of mineral resources in Amazon), by Veiga (1999), emphasized how understanding the types and distributions of geological features can inform resource management and conservation practices, highlighting Brazil’s geodiversity as a reservoir of natural resources and a foundation for geological heritage (Veiga, 1999).

Nevertheless, it was the work of Nascimento *et al.* (2008) that really started the present-day sequence of studies on geodiversity in Brazil. The book, titled “Geodiversidade, Geoconservação e Geoturismo: Trinômio importante para a proteção do patrimônio geológico” (Geodiversity, Geoconservation and Geotourism: an important trinomial for the protection of geoheritage), represents a milestone on the topic. The text addresses the importance of geodiversity and its intrinsic relationship with the

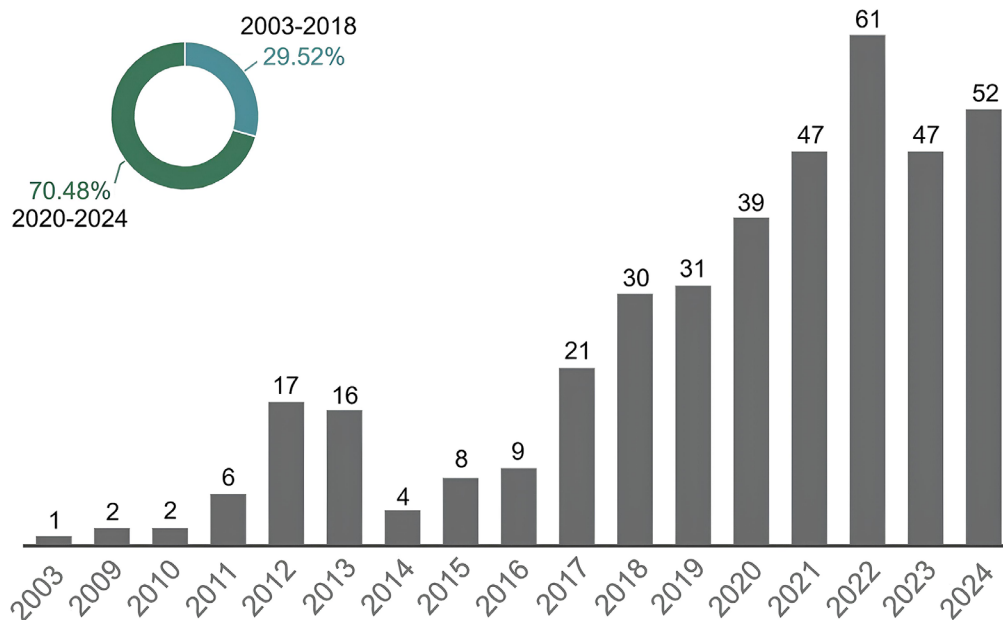


Figure 2 Papers published on the theme of geodiversity and correlated between 2003 and 2024.

conservation of geological heritage. The author emphasizes that geodiversity is fundamental for understanding not only the history of the Earth but also for preserving biodiversity and ecosystems. Geoconservation is discussed as an essential practice for the protection of geological items, deserving attention in both the scientific sphere and in the realm of public policies.

Another watershed was the work of the Brazilian Geological Survey (CPRM/SGB, 2008), titled “Geodiversity of Brazil: knowing the past to understand the present and predict the future” (Geodiversidade do Brasil: conhecendo o passado para entender o presente e prever o futuro), organized by Silva in 2008. This study started a new stage related to the research about geodiversity in the country, considering that it discussed not only geology but also geomorphology and landscape evolution by widening the range of analysis of regional geodiversity.

After these publications, an array of studies in terms of local and regional sites appeared in the Brazilian scenery. An interesting paper,

taking the geodiversity as a geological totality, appeared in 2015, with the title “Essa tal de geodiversidade...” (This so-called geodiversity...), from Machado and Azevedo (2015). This article presents, succinctly, the concept of geodiversity, asserting that as studies on the subject advanced, associated concepts emerged that clarify this new stance from part of the geoscientific community, including geosite, geoheritage, geoconservation, geotourism, and geopark.

One significant contribution to this field is the work of Silva *et al.* (2021), who, more than a decade later in relation to the precedent works, conducted a comprehensive review of the geodiversity in Brazil. Their paper, “Geodiversity in Brazil: Quantification, distribution and implications for conservation areas” published in *Geoheritage*, emphasizes the need for increased awareness and conservation efforts surrounding Brazil’s geological assets. The authors argue that protecting geodiversity is essential for maintaining the biodiversity that depends on these abiotic elements.

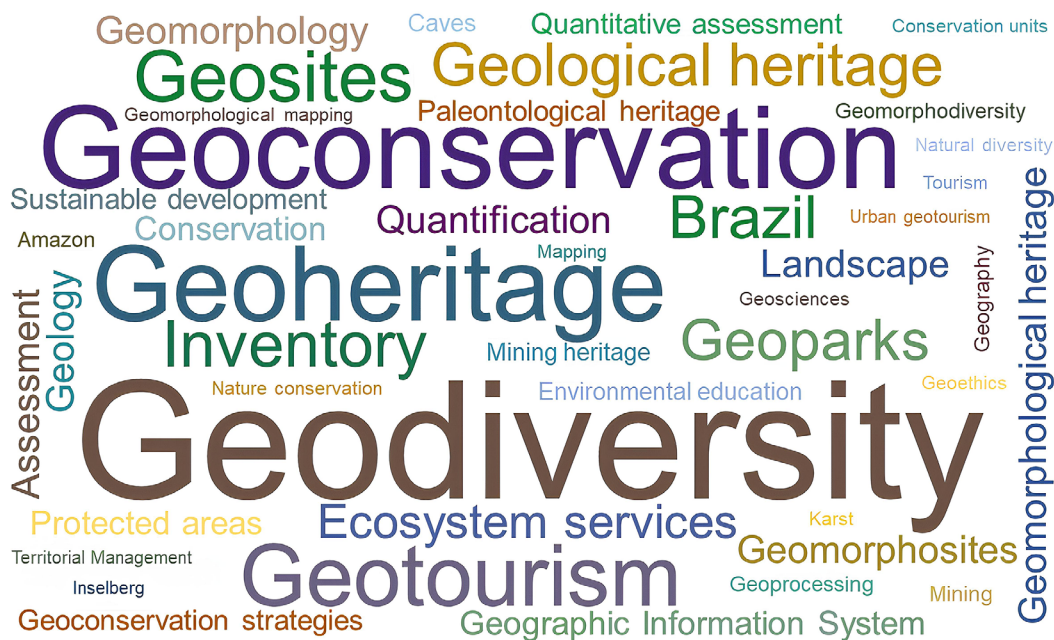


Figure 3 The words that were most repeated in the keywords plus of the papers for the years 2003-2024.

Table 1. The most cited articles on the research about geodiversity between 2003 and 2024.

Paper	Total Citations
Pereira, D.I., Pereira, P., Brilha, J., Santos, L., 2013, Geodiversity assessment of Paraná State (Brazil): an innovative approach: <i>Environmental management</i> , 52, 541-552. https://doi.org/10.1007/s00267-013-0100-2	139
Mucivuna, V.C., Reynard, E., Garcia, M.D.G.M., 2019, Geomorphosites assessment methods: comparative analysis and typology: <i>Geoheritage</i> , 11, 1799-1815. https://doi.org/10.1007/s12371-019-00394-x	79
Silva, J.P., Rodrigues, C., Pereira, D.I., 2015, Mapping and analysis of geodiversity indices in the Xingu River basin, Amazonia, Brazil: <i>Geoheritage</i> , 7, 337-350. https://doi.org/10.1007/s12371-014-0134-8	52
Silva, J.P., Pereira, D.I., Aguiar, A.M., Rodrigues, C., 2013, Geodiversity assessment of the Xingu drainage basin: <i>Journal of Maps</i> , 9(2), 254-262. https://doi.org/10.1080/17445647.2013.775085	50
Santos, D.S., Mansur, K.L., Gonçalves, J.B., Arruda Junior, E.R., Manosso, F.C., 2017, Quantitative assessment of geodiversity and urban growth impacts in Armação dos Búzios, Rio de Janeiro, Brazil: <i>Applied Geography</i> , 85, 184-195. https://doi.org/10.1016/j.apgeog.2017.03.009	50
Forte, J.P., Brilha, J., Pereira, D.I., Nolasco, M., 2018, Kernel density applied to the quantitative assessment of geodiversity: <i>Geoheritage</i> , 10, 205-217. https://doi.org/10.1007/s12371-018-0282-3	48
Pellitero, R., Manosso, F.C., Serrano, E., 2015, Mid-and large-scale geodiversity calculation in Fuentes Carrionas (NW Spain) and Serra do Cadeado (Paraná, Brazil): methodology and application for land management: <i>Geografiska Annaler: Series A, Physical Geography</i> , 97(2), 219-235. https://doi.org/10.1111/geoa.12057	44
Silva, M.L.N., Nascimento, M.A.L., Mansur, K.L., 2019, Quantitative assessments of geodiversity in the area of the Seridó Geopark Project, Northeast Brazil: Grid and centroid analysis: <i>Geoheritage</i> , 11, 1177-1186. https://doi.org/10.1007/s12371-019-00368-z	42
Santos, I., Henriques, R., Mariano, G., Pereira, D.I., 2018, Methodologies to represent and promote the geoheritage using unmanned aerial vehicles, multimedia technologies, and augmented reality: <i>Geoheritage</i> , 10, 143-155. https://doi.org/10.1007/s12371-018-0305-0	39
Moreira, J.C., 2012, Interpretative panels about the geological heritage - a case study at the Iguassu Falls National Park (Brazil): <i>Geoheritage</i> , 4(1), 127-137. https://doi.org/10.1007/s12371-012-0053-5	34
Garcia, M.D.G.M., 2019, Ecosystem services provided by geodiversity: Preliminary assessment and perspectives for the sustainable use of natural resources in the coastal region of the state of São Paulo, Southeastern Brazil: <i>Geoheritage</i> , 11(4), 1257-1266. https://doi.org/10.1007/s12371-019-00383-0	32

From there, the continuation of the research on geodiversity in Brazil, as already pointed out, opened to a large range of elements, especially linked with geomorphodiversity. Lately, pedological and hydrological research has enlarged this spectrum. In this section, the state of the art is presented for each abiotic element that characterizes Brazil's geodiversity—that is, its geological, geomorphological, hydrological, pedological, and climatic diversity—and the related studies, as discussed in the following paragraphs.

In terms of geological diversity—called “geolodiversity” by Claudino-Sales (2024)—Brazil stands out as a marvel, characterized by an extensive array of geological formations, processes, and minerals that contribute to its rich geodiversity. Effectively, Brazil's geodiversity encompasses a range of geological formations,

from ancient Precambrian shields to expansive sedimentary basins, each shaped by various geological processes, including tectonics, erosion, and sedimentation. Research on geolodiversity in Brazil highlights the country's complex geological history, which is essential for understanding natural resources, environmental processes, and landscape evolution.

The geolodiversity of Brazil, in terms of scientific and technical production, has been worked by the Brazilian Geological Survey (CPRM/SGB, 2008). The SGB has published maps, reports, papers, and technical documents, thereby disseminating the country's geological diversity. The organization also created a website to register the occurrence of geosites in the Brazilian territory and is working closely with the universities and municipalities on the creation of geoparks in all Brazilian regions.

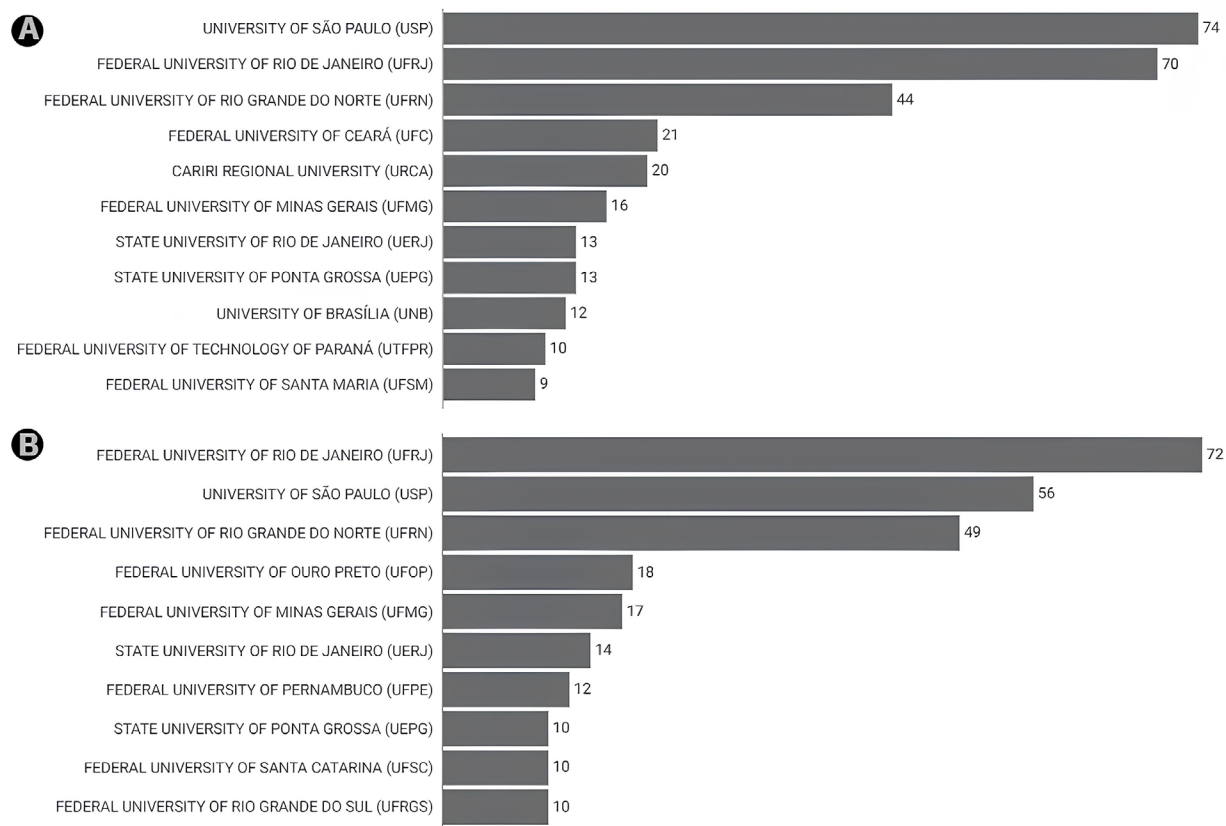


Figure 4 More frequent affiliations of the authors. A. Web of Science (WoS); B. Scopus.

The geolodiversity is also a subject of attention of the Brazilian Society of Geology (SBG), which encourages activities linked to the subject. Pereira *et al.* (2016), for example, in a paper named “Geodiversidade e Geopatrimônio: ferramentas para a educação e disseminação das Geociências” (Geodiversity and Geoheritage: tools for education and dissemination of Geosciences), present the result of an experience at a middle school in Brazil, in agreement with the SBG, to disseminate the geosciences and foster the practice of identifying geological sites in the countryside, seeking to preserve Brazilian geological heritage. The theme is also present in the Geology Congresses organized by the association, which take place in Brazilian territory frequently.

Another contribution to Brazilian geolodiversity is the paper “Geological diversity fostering actions in geoconservation: An overview of Brazil”, written by Garcia *et al.* (2022). The paper links the geodiversity of Brazil with the geological evolution of the South American Platform, aiming to present the geological bases that generated the geodiversity of the country and trace an overview of how geodiversity is being approached locally in the light of geoconservation and its relationship with biodiversity.

A recent paper presented links between geodiversity and mining, considering a geopark territory. It is the study of Costa *et al.* (2024), named “Correlating geodiversity and mining in the Seridó UNESCO Global Geopark: Spatial and impact analysis in Brazilian Northeast”, published by Resources Policy, that aims to assess the impact of mining on the geopark’s geodiversity and geoheritage. Through cartographic analysis, mineral resources and mining areas observations overlapping with geodiversity mapping, geosites’ proximity to exploration areas, and abiotic ecosystem services generated or interrupted by mining, the results showed a wide diversity of resources and different relationships between geodiversity hotspots, geosites, and mining areas.

In terms of geomorphodiversity, research has gained significant attention due to Brazil’s complex and varied landscapes. Its geomorphodiversity encompasses a large range of landforms, including mountains, plateaus, valleys, river basins, and coastal features. This diversity not only represents a significant aspect of Brazil’s natural heritage but also has implications for environmental management and land use.

A publication that argues for the identity of geomorphological heritage itself, e.g. not only

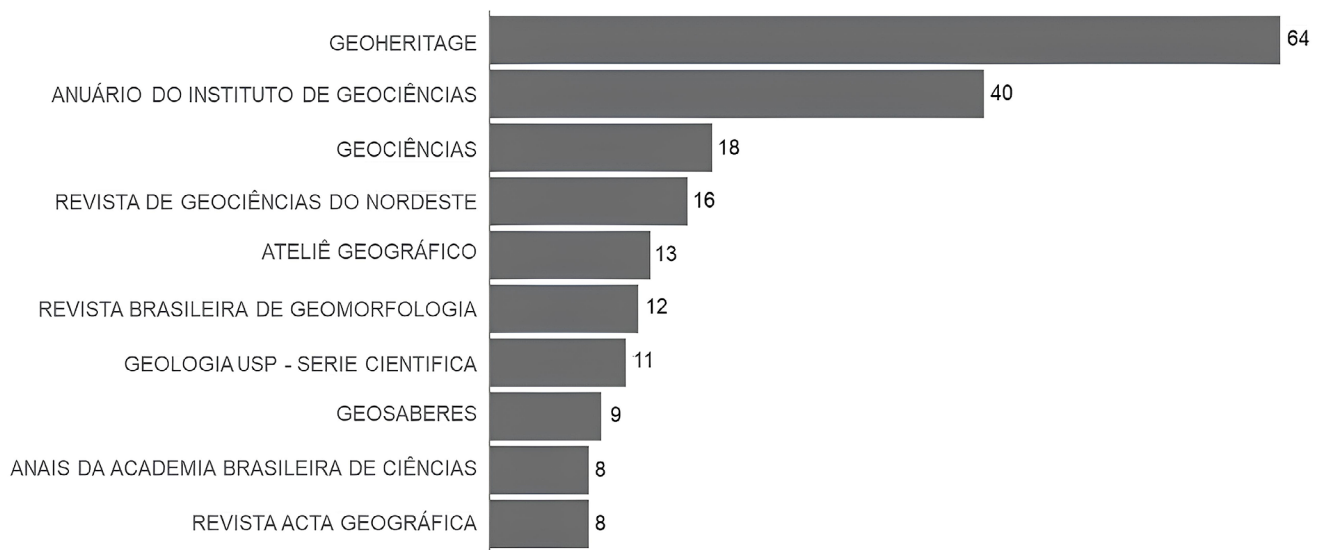


Figure 5 Journals where international papers on geodiversity were published by Brazilian researchers.

linked to geodiversity, and having Brazil as an example, was that of Claudino-Sales (2018), named “Morfopatrimônio e morfodiversidade: pela afirmação do patrimônio geomorfológico strictu sensu” (Morphoheritage and morphodiversity: for the affirmation of the geomorphological heritage strictu sensu). The paper aimed to allow progress in the theme of geomorphology heritage, lately called geomorphodiversity and geomorphoheritage (Claudino-Sales, 2021b). It also proposes the expansion of the typology of geomorphosites, defining the existence of sedimentary geomorphosites, crystalline geomorphosites, coastal geomorphosites, fluvial geomorphosites, and karst geomorphosites.

It can be said that the research on geomorphodiversity in Brazil encompasses a wide array of studies that analyze the country’s diverse landforms and their implications for natural resource management, conservation, and economic activities, having hydrographic basins, municipalities, different biomes’ territories, states territories and geographical regions as spatial scale.

The number of studies in this sense is growing, and the body of literature underscores the importance of geomorphodiversity in geodiversity research, as well as the broader context of environmental sustainability and policymaking in Brazil.

One important publication in this direction appeared in 2024, under the title “Patrimônio geomorfológico brasileiro: análise das publicações sobre inventários de geomorfossítios” (The Brazilian geomorphological heritage: analysis of publications on geomorphosites inventories), by Mazzucato *et al.* (2024). The paper aimed to provide an overview of the main characteristics of research on geomorphological heritage in Brazil. As a result, the authors found out that 30 works on the topic were published between 2013 and 2022, including papers, dissertations and theses. The results show the gradual increase in research activity on the theme, mainly concentrated in the Northeast and Southeast regions.

In the year 2024, another important paper was published, aiming to apply and compare the spatial distribution of the geodiversity indices

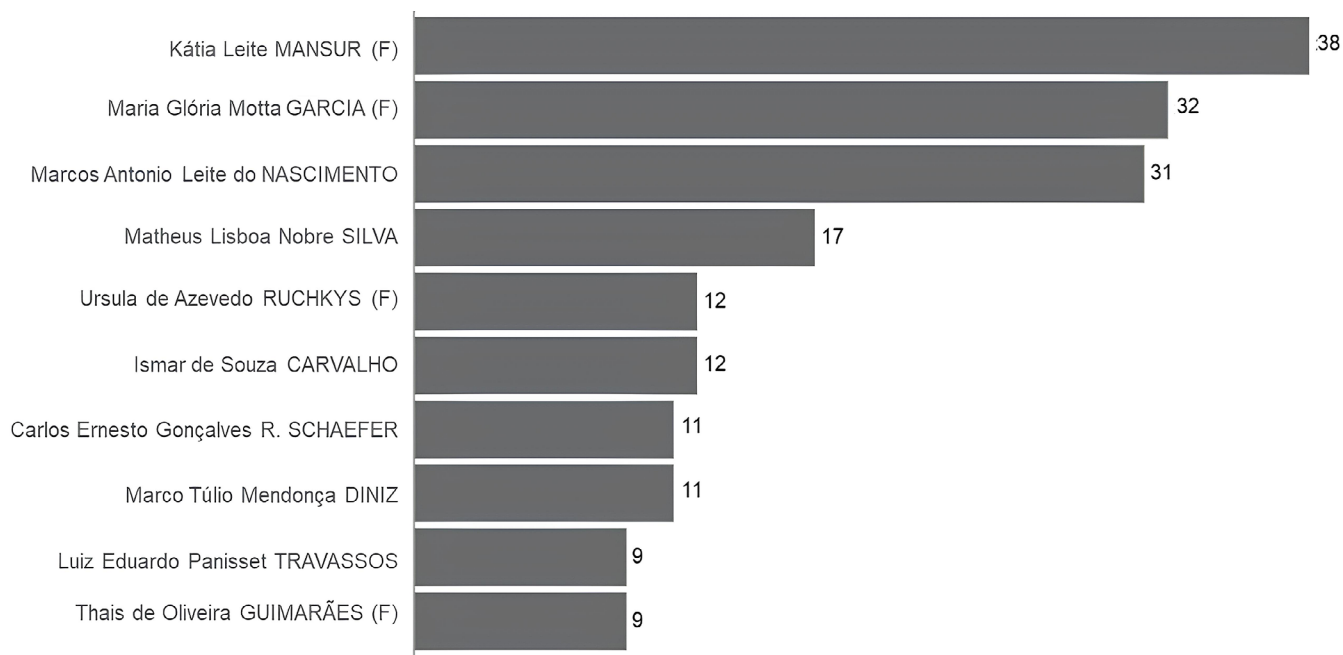


Figure 6 Authors with the highest number of papers published about geodiversity.

derived from four methodologies in the Brazilian Amazon. Silva *et al.* (2024), in this analysis, seek to understand the distribution of the geodiversity indices in the Brazilian Amazon and organize a cartographic base for future correlations with spatial data representative of biodiversity and human appropriation of the territory. The comparison between the quantitative indices showed some tendencies in the spatial patterns of geodiversity of the Brazilian Amazon but also presented indications of the limitations imposed by the different measurement criteria of the abiotic variables used.

In terms of pedodiversity, Brazil's vast territory encompasses various climatic and geological conditions that contribute to diverse soil formations, making it an ideal area for studying pedoheritage. Indeed, research on pedodiversity and pedoheritage in Brazil is crucial for understanding the intricate relationships between soil types, their historical significance, and their role in supporting both biodiversity and human cultures. Nevertheless, there are not many studies on the topic.

An important publication is that of Botelho (2021), "Brazilian soil heritage inventory" (Inventário do Patrimônio Pedológico no Brasil), who considered that soils have received insufficient attention as abiotic heritage in the country, as well as in the world. The author points out that pedodiversity needs to be identified, valued and protected. The paper presents the inventory of the Brazilian soil heritage, showing that it comprises a total of 604 pedosites and represents an effort to recognize the soil as geoheritage in the country.

Botelho, together with Lira (Lira and Botelho, 2023), also presented a detailed classification of pedodiversity and pedosites in the state of Rio de Janeiro. The work consists of the analysis of soil data from the Environmental Database and Information (BDIA) of Brazilian Institute of Geography and Statistics (IBGE). The authors pointed out that, considering the territorial area of Rio de Janeiro, which represents only 0.51% of the country, it can be considered that the state has high pedodiversity.

Another regional study had already been conducted in 2018 by Silva *et al.*, presenting the pedodiversity of the state of Minas Gerais. The authors worked with taxonomy information from the Soil Map of the state of Minas Gerais, scale 1: 650,000, and the pedodiversity was calculated for the biomes and the geomorphological units present in the territory of this state. At the end, a synthesis map of Minas Gerais pedodiversity was proposed.

Research on hydrodiversity linked to geodiversity in Brazil is as scarce as that on pedodiversity. Considering that hydrodiversity refers to the variety of water forms—including rivers, lakes, wetlands, and watersheds—within a given region and their associated ecosystems and cultural significance, it can be said that in Brazil, places like the Amazon River Basin, Pantanal wetlands, and the coastal areas reveal profound hydrodiversity. Effectively, as one of the most biodiverse countries in the world, Brazil boasts a rich tapestry of ecosystems shaped by its varied geological context and abundant water bodies. Nevertheless, research linking water as an element of geodiversity and abiotic heritage (hydroheritage) is not yet very common.

A rare work is that of Águas e Silva (2021), named "Os saberes das águas: interculturalidade e sócio-hidrodiversidade no Cerrado brasileiro" (Water Knowledges: Interculturality and Socio-Hydrodiversity in the Brazilian Savanna). This article describes the socio-hydrodiversity of Indigenous and traditional peoples in the Tocantins-Araguaia basin (Center-West region of Brazil), with the dual objective of recognizing their knowledge of the waters and opposing these perceptions to the dominant models of agro-export and of mega-hydraulic developmentalism.

More recently, Barbosa and Correia (2023) presented a study about hydrodiversity in the state of Rio Grande do Norte. The paper, titled "Trilhas educativas e hidrodiversidade: o caso das lagoas da FLONA de Nísia Floresta (RN)" (Educational trails and hydrodiversity: the case of the lakes of Nísia Floresta Flona, RN), indicated

that the lakes provide environmental services such as groundwater recharge, habitat for species of amphibians, reptiles, fish and crustaceans, feeding areas for birds and mammals, and maintenance of the vegetation cover, highlighting thereby the importance of hydrodiversity for the local environment.

The hydrodiversity was also the object of the paper of Oliveira *et al.* (2017), named “Proposal for classifying the relevance of waterfalls as a subsidy for the conservation of natural heritage” (Proposta de Classificação de Relevância de Quedas d’água como subsídio à conservação do patrimônio natural). The authors propose a protocol to classify the relevance of waterfalls to support the environmental legislation. The protocol has been field-tested in 20 (twenty) of the most important and recognized scenic beauty waterfalls of the Estrada Real section in Minas Gerais, aiming to verify if the criteria, theoretically raised by experts—Delphi technique—was consistent with reality. The paper showed that it was possible, through a multi-criteria method for analysis decision, to create a waterfalls classification protocol according to their relevance.

The other element of the abiotic environment linked to geodiversity, the climate, has not yet been an object of research in Brazil. Although climodiversity can be understood as the variation in climatic conditions (such as temperature, precipitation, and wind patterns) across different regions or habitats—and therefore linked to traditional climatology—its relevance within the broader framework of climatic geodiversity, encompassing climosites and climoheritage, has been little explored in the literature.

Claudino-Sales (2024) suggested that situations such as the occurrence of humid climate in the Brazilian semiarid, related to the existence of mountains, or the presence of the local wind called “Minuano” by the people from the extreme south of Brazil (state of Rio Grande do Sul), as well as the wind “Aracati” in the coastal area of Ceará State, in the Northeast region, could be considered a type of immaterial climosite and a particular

situation of climoheritage. The researcher also pointed out that many other situations of specific climatic conditions exist in Brazilian territory and that research in this direction is certainly going to develop in the next few years.

Besides the studies related to the elements that form the abiotic environment – what implies a geographical reading of geodiversity, as pointed out by Claudino-Sales (2021a, 2024), Brazilian researchers have also produced a significant number of case studies, analyzing the geodiversity in hydrographical basins, municipalities limits, geomorphological features, regional divisions, geoparks, and in a large variety of geological, geomorphological, hydrological, pedological and climatic contexts. Studies developed in the presentation of geodiversity indexes are also an important element of the scientific production on the subject in Brazil in the last decade.

6. Recent advances in geodiversity research in Brazil

Several challenges and research gaps persist in the study of geodiversity in the country. Nevertheless, it is important to highlight that efforts are being made in the sense of assessing geodiversity values in a more effective way. They are for example, essays for the application of new methodologies, showing that there are still possibilities for the growth and increasing of productivity in the topic in the direction of applicability and social uses of geodiversity research. Many studies, as exemplified below, are proof of this motivational situation.

The research of Silva (2022) seeks to apply ecocentrism – it means a philosophy that places nature and not humans in the center of the world – in a qualitative-quantitative assessment of geodiversity. The results show sites where human benefits appear to be predominant but also show places where the benefits offered by geodiversity to the environment, in maintaining environmental balance and protection and reproduction of life,

are the main ones. This study brings new insights into the way of looking at geodiversity and society itself and represents a new tendency in the context of the impacts of climatic and environmental changes of the XXI century.

Another new study was proposed by Araújo *et al.* (2024), related to a method and a proposal for an inventory of the geomorphological heritage. The methodological proposal was elaborated after reviewing specialized literature on the subject, and consists of three main stages: site selection, qualitative evaluation and quantitative evaluation. For that, an extensive form detailing structures, processes and geofeatures was developed and presented. The methodology has already been tested in several graduation research projects and has the potential to strengthen the studies and production of geomorphoheritage.

An innovative study was presented by Terto *et al.* (2024) related to hydrodiversity. Published in the journal “Geomorphology”, the article proposes a comprehensive methodology for the analysis of hydrological heritage, structured to address scientific, sociocultural, aesthetic, and touristic values. The methodology proved satisfactory in assessing water resources, considering their relevance in an environmental and social context, besides being an integral part of geodiversity.

From a general point of view of geodiversity studies, there is the publication of Moura and Claudino-Sales (2024) related to the occurrence of geosites of the type “overview”, which were considered by the authors as “panoramic geosites”. The study was conducted in the Northeast region of Brazil and introduces a new type of approach for geodiversity in mountainous landscapes.

These innovative methodologies enhance the ability to study geodiversity at unprecedented scales in Brazil, allowing researchers to analyze geodiversity hotspots and assess their ecological significance. These innovations are crucial for conservation efforts, potentially helping to identify areas that require protection due to their rich geological and biological resources.

7. Conclusions

Geodiversity research in Brazil is a growing field with significant implications for environmental management, conservation, and biodiversity. Ongoing studies reveal the complex relationships between geological features and ecological dynamics. Addressing existing gaps will be crucial for safeguarding Brazil’s rich natural heritage, enhancing our understanding of ecosystems, and informing sustainable development policies.

Indeed, addressing knowledge gaps and fostering interdisciplinary collaboration will be key to ensuring that Brazil’s geoheritage is preserved in an era of rapid environmental changes. One significant thing is the data gaps in remote areas. Many regions, particularly in the Amazon, remain understudied, hindering a comprehensive understanding of geodiversity. In addition, climate change poses a risk to the integrity of national geodiversity, especially when considering that the long-term effects of climate change on geodiversity are not yet well understood.

Effectively, there is a critical need for long-term studies assessing geodiversity and its changes over time, primarily driven by climate change and human impacts. In addition, effective policies for the management and conservation of geodiversity in the Brazilian territory are still lacking, highlighting the need for interdisciplinary approaches to policymaking (Presidência da República do Brasil, 2006).

To advance geodiversity research in Brazil, future studies should adopt integrated approaches that combine abiotic, ecological, and socio-economic perspectives to promote a more holistic understanding and support the development of more effective conservation policies. Further research is also required to assess the effectiveness of existing legislation on geodiversity conservation and its implementation at the local level. Moreover, the establishment of educational initiatives and public awareness campaigns are essential to enhance society’s understanding and appreciation of the importance of geodiversity.

This comprehensive state of the art was structured to reflect a thorough review of geodiversity research in the country, highlighting significant contributions and establishing a basis for future research directions. Here, it is believed that, as Brazil faces environmental challenges, geodiversity research will play a pivotal role in guiding sustainable practices and informing policy decisions.

Contributions of authors

(1) Conceptualization: VCS; (2) Analysis or data acquisition: ACDSS, IGDA; (3) Methodologic/technical development: ACDSS, IGDA, MTMD; (4) Writing of the original manuscript: VCS, ALHS; (5) Writing of the corrected and edited manuscript: VCS, MTMD, ALHS, ACDSS, IGDA; (6) Graphic design: ACDSS, IGDA; (7) Fieldwork: not applicable; (8) Interpretation: MTMD.

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Conflicts of interest

The authors declare that there is no conflict of interest.

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