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A scientometric review of research on saprolite in Brazil from 1990 to 2022[1]

Uma revisão cienciométrica da pesquisa sobre saprolito no Brasil de 1990 a 2020

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HIGHLIGHTS:

The Brazilian Amazon Basin captures 25% of the Silicate C Sink but had the smallest number of saprolite papers.
A total of 57.22% of the papers were published in the last decade.
The main groups of saprolite research were "pedology", "geochemistry" and "landscape".

ABSTRACT: The consumption of atmospheric carbon dioxide by weathering buffers the greenhouse effect on Earth on a geological timescale. This mechanism is called the silicate carbon sink (SCS). Saprolite represents part of the weathering front of the Earth's mantle, but historically, it has not received much attention from geoscientists. On a global scale, Brazil is the largest contributor to the SCS and the fourth largest contributor to the number of saprolite publications. In this study, Brazilian scientific production on the subject from 1990 to 2022 was assessed, considering publications indexed in the Web of Science, SciELO and Scopus databases. One hundred-eighty scientific articles were retrieved. In the last decade, seven articles were published per year. Over the 32 years under consideration, the number of articles on saprolite has increased. Most of the studies were concentrated in the southeastern region of Brazil, where the state of Minas Gerais led in terms of the number of publications (28.49%). The main areas in which the articles were published were related to ecology, Earth, and marine; however, they were cited by several others, including the areas of health and politics. A comparison of the number of publications per basin and the size of the SCS showed that there were fewer studies from the Amazon Basin than from the Paraná Basin. In conclusion, the geographical frontier for the study of saprolite in the Brazilian territory is the Amazon River Basin, and the methodological frontier is related to fluid/gas dynamics and the role of microbes in weathering at depth.

Key words: isalterite, isoalterite, CiteSpace, science mapping, visual analytics

RESUMO: O consumo de dióxido de carbono atmosférico pelo intemperismo tampona o efeito estufa na Terra em escala de tempo geológica. Esse mecanismo é chamado de sumidouro de carbono de silicato (SCS). Saprolito representa parte da frente de intemperismo do manto terrestre, mas historicamente não recebeu muita atenção dos geocientistas. Em escala global, o Brasil é o maior contribuinte para o SCS e o quarto maior contribuinte em número de publicações sobre saprolito. Neste estudo, a produção científica brasileira sobre o assunto de 1990 a 2022 foi avaliada, considerando publicações indexadas nas bases de dados Web of Science, SciELO e Scopus. Foram recuperados cento e oitenta artigos científicos. Na última década, sete artigos foram publicados por ano. Ao longo dos 32 anos considerados, o número de artigos sobre saprolito aumentou. A maioria dos estudos foi concentrada na região sudeste do Brasil, onde o estado de Minas Gerais liderou em termos de número de publicações (28,49%). As principais áreas em que os artigos foram publicados estavam relacionadas à ecologia, Terra e marinha; no entanto, foram citados por várias outras, incluindo as áreas de saúde e política. Uma comparação do número de publicações por bacia e o tamanho do SCS mostrou que havia menos estudos da Bacia Amazônica do que da Bacia do Paraná. Em conclusão, a fronteira geográfica para o estudo do saprolito no território brasileiro é a Bacia do Rio Amazonas, e a fronteira metodológica está relacionada à dinâmica de fluídos/gases e ao papel dos micróbios no intemperismo em profundidade.

Palavras-chave: isalterita, isoalterita, CiteSpace, mapeamento científico, análises visuais

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Introduction

Using scientometric analyses, it is possible to comprehend the progress of science in several fields (Souza et al., 2022; Tao et al., 2022). These analyses measure the contribution of publications in certain areas to evaluate the performance and influence of researchers, regions and research institutions (He et al., 2019; Akbari et al., 2020), in addition to evaluating the development of research areas (Lee et al., 2016).

Scientometrics has already been applied in the areas of soil health (Liu et al., 2020) and soil quality (Martini et al., 2020) and in the general context of soil science (Mokhnacheva et al., 2020). However, as the saprolitic zone is most likely the least known part of the critical zone, a scientometric study can identify consolidated areas and, by contrast, areas that need more research.

Saprolite is the material resulting from in situ isovolumetric weathering of the bedrock surface (Phillips et al., 2019; Silva et al., 2022), which develops between the solum (horizon A+B of the soil) and undisturbed rock. Saprolite performs several fundamental functions in the environment (Santos et al., 2022a), including carbon sequestration, by mechanisms such as the formation of pedogenic carbonates (Manning et al., 2013).

Brazil is the main country that consumes CO_2 via the silicate carbon sink (SCS), accounting for 24.41% of the global total (Zhang et al., 2021; Xiong et al., 2022). This is because the distribution area of silicate rocks in the Amazon and Paraná River Basins is among the largest in the world and among the five largest basins in terms of the SCS (4.46 and 2.58 Tg/year, respectively) (Zhang et al., 2021). This paper describes the scientific literature based on the number and content of published papers from 1990 to 2022, indexed in the Web of Science, SciELO and Scopus.

Material and Methods

The data used were obtained from three platforms: Web of Science Main Collection Clarivate Analytics (WOS) <https://www.webofscience.com/wos/alldb/basic-search>, Elsevier SciVerse Scopus <https://www.scopus.com/search/form.uri?display=basic#basic> and Scientific Electronic Library Online (SciELO) <https://analytics.scielo.org/?journal=clean>. The three abovementioned platforms were chosen to expand the scope since some Brazilian journals are not indexed on the Web of Science. In addition, these platforms contain all bibliographic data on citations, journals, keywords and other resources that can be used in scientometric analyses.

The data were collected using a set of keywords ("SAPROLIT*" OR "ISALTERIT*" OR "ISOALTERIT*") through the CAPES/MEC portal <http://www-periodicos-capes90gov-br.ez11.periodicos,capes.gov.br>. Using the asterisk (*) for truncation, it was possible to retrieve articles with keywords in Portuguese, such as "saprolito", "saprolítico", and "saprólito", and in English, such as saprolite and/or saprolithology. The search field was limited to "Topics", including the fields referring to the title, abstract and keywords. Subsequently, the search was restricted only to research carried out in Brazil through the "Countries/Regions" tab. The search covered the period from January 1st, 1990, to June 30th, 2022, limited to scientific articles written in English and Portuguese. Publications in conferences, editorials, letters, meetings, books and book chapters, for example, were not considered.

A total of 406 articles were obtained from the three platforms mentioned above. The sequences were downloaded in ".txt" format. After this process, the articles were manually reviewed to identify duplicate entries, resulting in 180 records for the study sample in this paper. Since the databases do not provide data regarding research institutions, the 180 articles were manually verified to identify the place of research and the Brazilian state in which the first author holds a professional position. Some studies used samples collected in several states, which were counted and added to the research location data, totaling a final sample of 193 locations. The software used in the current study was CiteSpace, Version 6.1.R3, available for free at <https://citespace.podia.com/download>. CiteSpace is Java-based software developed by Dr. Chaomei Chen at the School of Information Science and Technology at Drexel University, USA. It allows researchers to explore and visualize emerging trends and fundamental changes in a certain focused field over time (Chen & Song, 2019; Chen, 2020).

For this study, the following variables were considered: i) number of publications over time, ii) number of articles published by state and iii) main research institution. These data were processed using RStudio software (R Core Team, 2016). CiteSpace (Chen, 2006) was used to create scientometric maps related to institutions, authors, country collaboration networks, journals, and double map overlays for journals and keywords. Through CiteSpace, it was possible to visually analyze trends and patterns in the scientific literature (Chen, 2014) based on mathematical and statistical methods (He et al., 2019).

The scientometric maps generated by CiteSpace are formed by links that connect to form nodes. Nodes can represent an author, a journal, a country, an institution, or keywords, among other choices of elements. Links describe the cocitation or co-occurrence between these nodes (Xie, 2015). The nodes are represented by a collection of rings in various colors, in which each color denotes the year a relationship was established. The closer to the node's center a relationship is, the older it is (Ouyang et al., 2018).

These nodes can be grouped together to form clusters. The homogeneity of these clusters can be evaluated through the silhouette coefficient (Eqs. 1 and 2) (Rousseeuw, 1987). This indicator is defined by the following equation:

$$S(i) = \{0,\ 1 - \frac{a(i)}{b(i), \text{if } a(i) < b(i)}, a(i) = b(i), \frac{b(i)}{a(i) - 1, \text{if } a(i) > b(i)}\} \quad (1)$$

where:

a(i) - the average distance of i from all other data within the same cluster;

b(i) is the smallest average distance of i from any other cluster for which i is not a member; and

S(i) is the silhouette coefficient ranging between [-1,1], as per Eq. 2.

$$-1 \le s(i) \le 1 \quad (2)$$

The value of a cluster silhouette (S) measures its configuration quality. It varies between [-1,1]. When the value is high, the cluster can be considered internally consistent and distinct from other clusters (Chen, 2014). Finally, the modularity index (Q) of the analysis was extracted, which indicates the extent to which the network is divisible into modules (Aryadoust et al., 2019). The value of Q ranges between [-1,1]. High values indicate that the clusters within the network are easily separable.

Results and Discussion

Brazil has the fourth-highest number of publications on saprolite, after the United States, France and Australia (Silva et al., 2022). There was significant variation in the number of publications on saprolite in the considered time window, with the greatest number of publications occurring in 2021 (with 20 articles) and the lowest number occurring in 1990, 1993, and 1994, in which no articles were found in 1994 (Figure 1).

Although the search covered 32 years spanning from 1990 to 2022, the first two articles were published in 1991. Both studies examined the changes in saprolite to clarify the origin of Belterra clay in northern Brazil (Truckenbrodt et al., 1991) and the formation of iron duricrust with gold in central Brazil (Oliveira & Campos, 1991). During the 1990s, 13 out of 180 articles (7.22%) were published. The small number of publications in this decade followed the worldwide trend found by Silva et al. (2022) in the same period. During this time, solum was the focus of most research, whereas saprolite was generally neglected (Brevik & Miller, 2015). In Brazil, the community of researchers who studied saprolite was very small.

Between 2000 and 2010, 58 of 180 articles were published (32.22%), and between 2011 and 2020, 74 of 180 articles (41.11%) were published. On average, 5 articles were published per year from 2000 to 2010, and 7 articles were published per year from 2011 to 2022 (Figure 1). This increase is known to be associated with the significance of saprolite in ecological and hydrological studies (Drahota et al., 2018; Nan et al., 2020).

By June 30th, 2022, 15 of 180 articles (8.33%) had been published. Considering the number of articles that had been published thus far, it was expected that by December 31, 2022, the number of articles should have exceeded 2021 (20 of 180 articles; 11.11%) (Figure 1). The significant increase in publications can be justified by the growing interest in the subject, aiming at understanding the genesis, evolution and dynamics of this underground zone (Santos et al., 2022b).

Connections were analyzed between the host state of the institution to which the researcher belonged (articles-author-state) and the state where the research was conducted (articles-research-state, Figure 2). The ratio between these two indices (articles-research-state and articles-author-state) indicated that for the states with ratios higher than 1.00 (Amazonas, index of 2.60; Rio Grande do Sul, 1.73; Minas Gerais, 1.45; Mato Grosso, 6.00; Pernambuco, 1.43; Paraná, 1.33; Espírito Santo, 1.33; Santa Catarina, 1.00; Ceará, 1.00; and Maranhão, 1.00), there was a predominance of researchers who carried out their studies on saprolite located in their own state. The states that had indices lower than 1.00 (Pará, 0.83; Rio de Janeiro, 0.81; Distrito Federal, 0.71; São Paulo, 0.58 and Goiás,

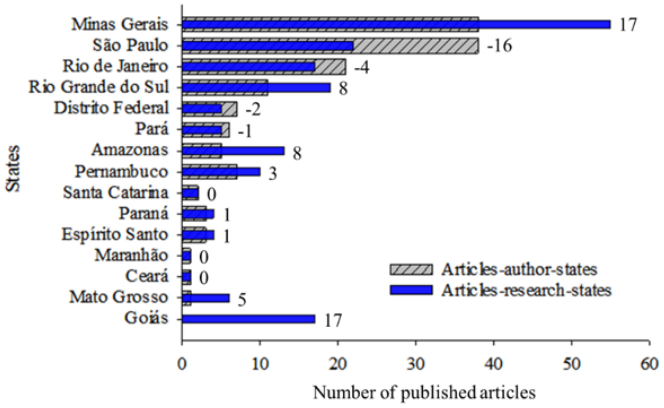


Figure 2. Comparison between the number of articles published by corresponding authors belonging to institutes located in a state (articles-author-state) (gray bar) and the number of articles published in the state where the research was conducted (articles-research-state) (blue bar). In cases where the blue bar is greater than the gray bar, researchers studied saprolite located in the same state where the institute was located. Otherwise (gray bars greater than blue), the institute where the research was performed was not the same as where the saprolite was located

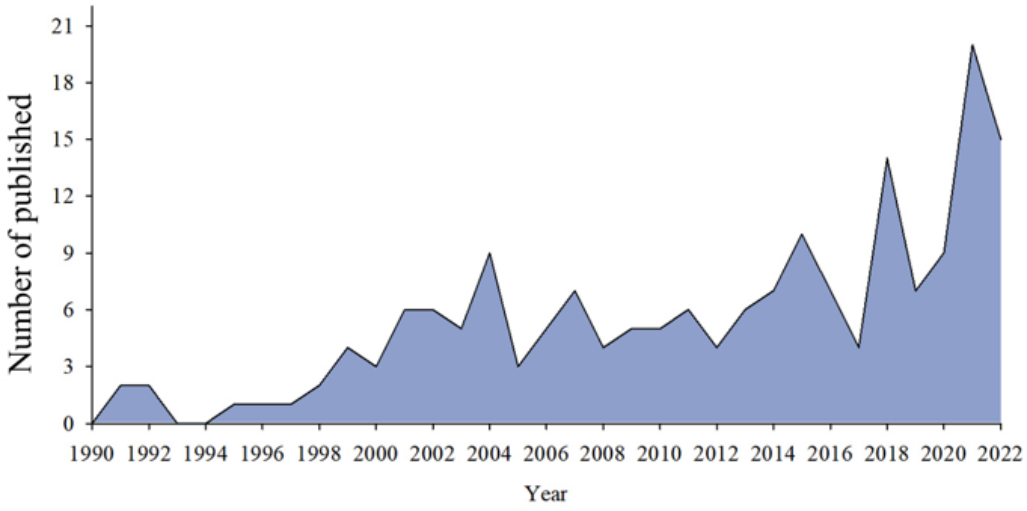


Figure 1. Visualization of scientific productions, distributed annually from 1990 to 2022

0.00) indicated that the published research was performed by resident researchers working on saprolite from another Brazilian state.

In the case of Goiás, all studies on saprolite were carried out by researchers from institutes in other states. The number of articles published by authors from institutes in São Paulo ranked first, along with Minas Gerais. However, São Paulo had the lowest ratio of articles-research-state/articles-author-state because these researchers carried out many studies on saprolites located in other states, emphasizing the importance of partnerships between researchers. The territory of the Amazonas, Pará and Mato Grosso states comprises 43.74% (IBGE, 2022) of the Brazilian surface area. However, those states had a small number of studies, indicating that the number of studies on saprolite was not linearly linked to territorial areas (Oliveira & Campos, 1991; Truckenbrodt et al., 1991; Horbe & Costa, 1997; Costa & Moraes, 1998; Horbe & Costa, 1999; Galarza & Macambira, 2002; Apoitia et al., 2004; Costa et al., 2004; Horbe et al., 2004; Nascimento et al., 2004; Oliveira & Larizzatti, 2005; Cornelius et al., 2007; Horbe et al., 2007; Larizzatti et al., 2008; Horbe & Anand, 2011; Novaes Filho, 2012; Agnoletto & Leite, 2015; Zenero et al., 2016; Prosdocimi et al., 2019; Mathian et al., 2020; Silva & Costa, 2020; Merdy et al., 2021; Negrão & Costa, 2021; Peixoto et al., 2021).

Figure 3 shows the geographic distribution of the research sites. Seven of the 180 identified articles used saprolite samples from different states of Brazil (Melo et al., 2001, 2002; Vasconcelos & Carmo, 2018; Santos et al., 2019a; Peixoto et al., 2021; Conceição et al., 2022; Santana & Botelho, 2022). The main hydrographic basins of Brazil are also presented in Figure 3 (Resolution nº 32 of the National Council of Water Resources, of October 15, 2003, CNRH, 2003). The limits of these river basins are delimited by differences in the country's ecosystems, as well as economic, social and cultural characteristics (Porto & Porto, 2008).

In the last 32 years (1990-2022), no studies on saprolite have been carried out in the states of Acre, Alagoas, Amapá, Rio Grande do Norte and Sergipe. Most of the studies were concentrated in the southeastern region (98 of 193 locations; 50.77%), with the largest number in the state of Minas Gerais (55 of 193 locations; 28.49%). The significant number of papers may be associated with the fact that the state of Minas Gerais is internationally recognized for the abundance of its geological resources, mainly iron ore and gold reserves (Silva, 2007).

Although Figure 3 shows the studies that were carried out in Brazilian states, it is not possible to know for sure which river basin each study was conducted. However, some states are located in a single basin, such as Rio de Janeiro, Tocantins, Rio Grande do Norte, Paraíba, Roraima, Acre, Amazonas, Rondônia and Amapá (the Southeast Atlantic, Tocantins-Araguaia, Eastern Northeast Atlantic and Amazon, respectively). Among these, Rio de Janeiro had the highest number of studies (17 of 193 locations; 8.81%).

The area occupied by silicate rocks in the Amazon and Paraná River Basins is among the 10 largest in the world (220.75 and 132.0 × 10^4 km^2, respectively) (Zhang et al., 2021). The Amazon Basin constitutes nearly a quarter of the planet's silicate carbon sink (SCS) (21.80 Tg/year). On the other hand, the Paraná Basin sequesters on average 2.58 Tg/year, second only to the Amazon Basin and the Zaire Basin in Africa. This result highlights the great lack of publications in the most

The different colors in the legend represent the hydrographic basins of Brazil

Figure 3. Number of articles published by Brazilian state

important river basins and, by extension, the greater number of SCSs on the planet. According to Figure 3, there were fewer studies on the Amazon River Basin than on the Paraná Basin. In this sense, advancing the characterization of the saprolite zone in these areas is essential since Brazil provides an advantageous environment for the weathering of silicate rocks (Xiong et al., 2022).

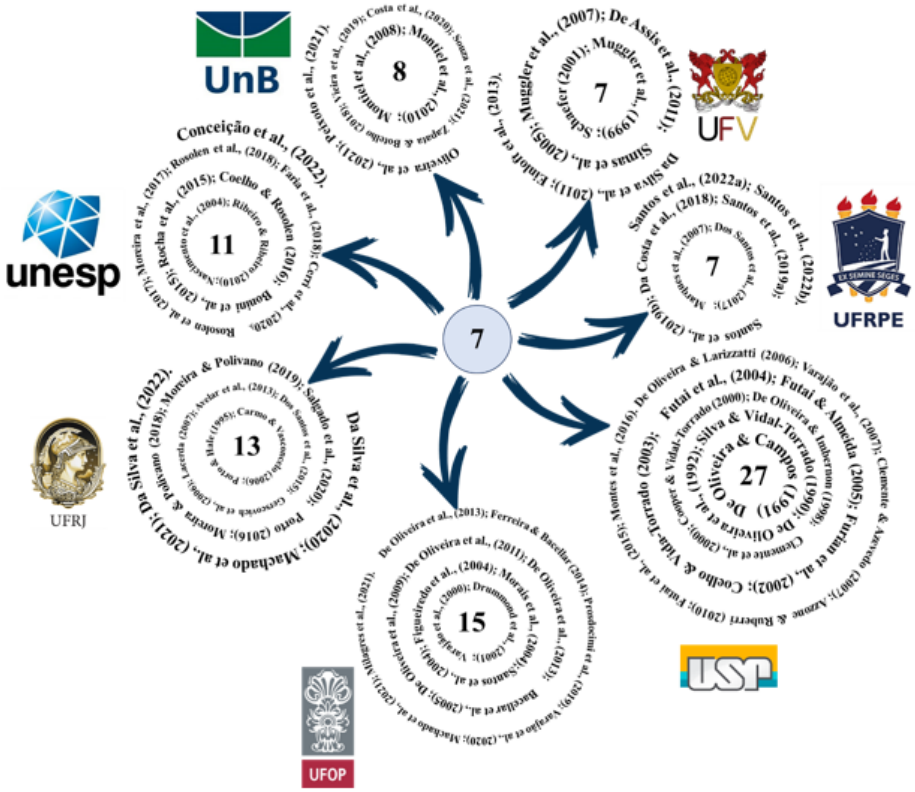
The seven main saprolite research institutions are listed in Figure 4. They were classified by the number of studies (center of the circles) on saprolite between 1990 and 2022, with emphasis on the authors (the circle rings) of the respective published articles. Among these, 43.67% of the articles were from two institutions in the state of São Paulo, followed by Minas Gerais (25.28%, two institutions), Rio de Janeiro (14.94%, one institution), and Distrito Federal and Pernambuco, both with only one institution (8.04%). All the institutions are public, and among them, three are maintained by state universities (USP and UNESP) and four are Federal Universities (UFOP, UFRJ, UFV, UNB and UFRPE).

The institutions generally correspond to field research locations. According to the data presented in Figure 2, Minas Gerais was the main state with the highest number of published articles (considering the institute of the corresponding author), along with the state of São Paulo. Figure 4 shows that the largest number of articles published came from institutions in the state of São Paulo (USP and UNESP; 38 articles). In this case, Minas Gerais changed its position when ranking the published articles with the scientific production of institutions. Several components can contribute to this phenomenon. Among them are each state investment in research (through research foundations or FAPs). For example, some FAPs allow funds to be applied to research projects conducted in other states, provided that the main researcher of the project belongs to an institution of the same state as that foundation. Other components are coauthorships, guidelines, and co-orientations.

The largest number of articles were published in Rio de Janeiro, and most of the articles were published by researchers from the UFRJ (13 out of 21 articles [61.90%]). According to the corresponding author, seven articles were published in the state of Pernambuco and the Federal District (Figure 2), which corresponds to the number of articles published by UFRPE and UNB.

Figure 5 further explores the partnerships between researchers, showing the network among institutions between 1990 and 2022 and highlighting the top 10 institutions. Each institution is represented by a node, and these nodes are represented by a series of rings in different colors. Each color represents the year of collaboration, and the thickness of the node is proportional to the number of partnerships. The colors of the links connecting the nodes represent the year of collaboration established between institutions.

All featured institutions began their saprolite research/partnerships in the 1990s, since the center of the nodes has a light grayish color (see color scale at the bottom of the graph). The same reasoning applies to the external part of the node for all institutions that have conducted research on saprolite in recent years, except for the UFV, UFSM and UFMG (these institutions lack a red outer ring). Partnerships between institutions are represented by links, in which each color represents the year in which the partnership was established.



Number of studies (center of circle) and authors (ring of circle) related to saprolite

Figure 4. Top 7 institutions with the greatest number of saprolite publications: UFV: Federal University of Viçosa; UFRPE: Rural Federal University of Pernambuco; USP: University of São Paulo; UFOP: Federal University of Ouro Preto; UFRJ: Federal University of Rio de Janeiro; UNESP: São Paulo State University "Júlio de Mesquita Filho"; and UNB: University of Brasília

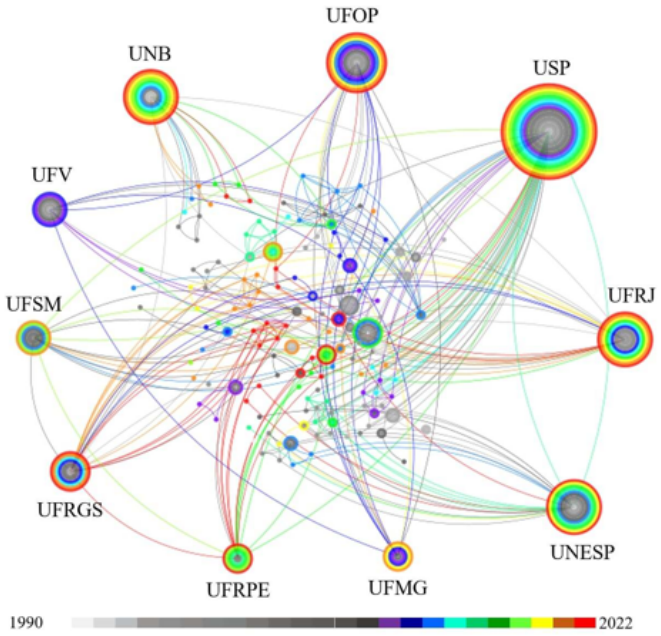


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Figure 5. Scientometric map of institution co-occurrence

The scientometric map displays links of varying colors, showing that Brazilian researchers have maintained partnerships over the 32-year span covered by the present study.

In the coauthorship map (Figure 6), each circle represents an author, and the links between two circles represent the collaboration between the authors, complementing the partnership between institutions presented in Figure 2.

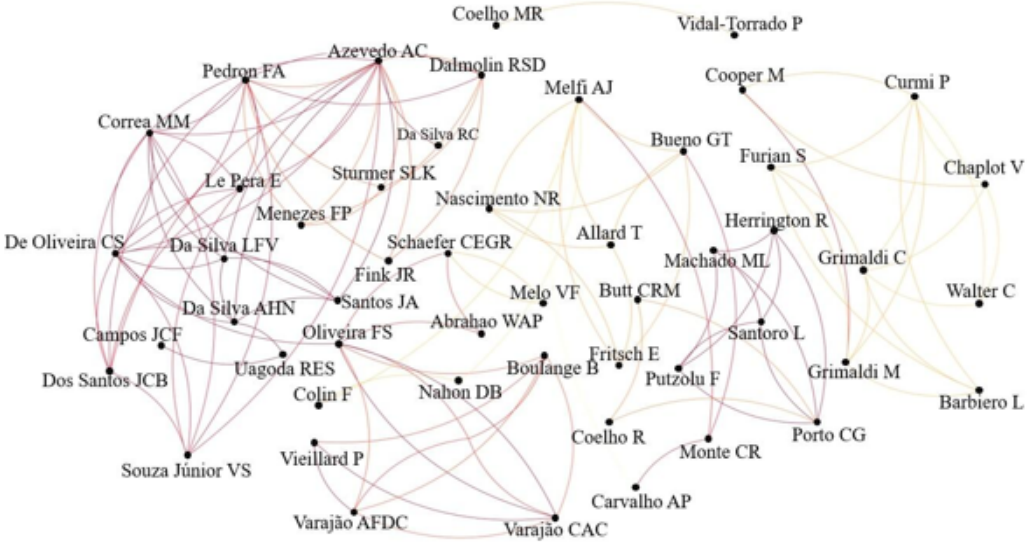
The size of the network between authors depends on the number of articles published and the line of action on saprolite-related topics. Authors with many articles have a large number of coauthorship relationships. The two main groups of coauthors consisted of 15 researchers—Azevedo AC, Correa MM, Silva AHN, Silva LFV, Silva RC, Dalmolin RSD, Oliveira CS, Santos JCB, Fink JR, Le Pera E, Menezes FP, Pedron FA, Santos JA, Souza Júnior VS and Sturmer SLK—and another of 8 authors—Curmi P, Barbiero L, Chaplot V, Cooper M, Furian S, Grimaldi C, Grimaldi M, and Walter C (Figure 6).

The group formed in the center of the network exhibited intricate connections, with Melfi AJ and Oliveira FS having the greatest collaboration. Only one group was formed by two authors (Coelho & Vidal-Torrado, 2003), which may be associated with a more specific line of study on saprolites. Most of the authors who are presented in this network are affiliated with the institutions presented in Figure 4.

Figure 7 shows the top 20 authors who had citation bursts in their documents during the 1990-2022 time span. In Figure 7, it is possible to identify the manuscripts that received attention from the scientific community, which occurred in the interval identified by the red line overlaid on the blue line (Shi & Yin, 2021; Ahmad et al., 2021).

The burst value was between 1.33 and 2.78, and the duration times were relatively short, except for three authors, Horbe AMC, Melfi AJ and Schaefer CEGR, who remained for a long period (10, 8 and 8 years, respectively). It is also noted that groups of authors had citation bursts in specific periods, mainly after 2011; for example, Boulange B, Oliveira FS, Varajão AFDC and Varajão CAC from 2011 to 2014. Among the 20 authors, 17 were Brazilian researchers. This group was composed mostly of agronomists (Azevedo AC, Correa MM, Dalmolin RSD, Santos JCB, Melo VF, Pedron FA, Schaefer CEGR and Vidal-Torrado P; 47.05%), followed by geologists (Costa ML, Oliveira SMB, Horbe AMC, Melfi AJ, Porto CG, Varajão AFDC and Varajão CAC; 41.17%) and geographers (Bueno GT and Oliveira FS; 5.88%).

Table 1 shows the 10 most cited articles and corresponding authors during the 1990-2022 time window. The saprolite topic is quite broad and has been used in several areas, with several different concepts (Ehlen, 2005). Thus, while the titles of the most referenced publications suggest a variety of methodologies and applications, the pedological approach dominates. For example, among the 5 most cited articles, 3 were published in journals that have the word "soil" in the title. It is also clear that all the articles were published in non-Brazilian journals. However, it is inferred that the "service life" of the articles was approximately 20 years, as was the effect of time



Source: CiteSpace - Own elaboration

Figure 6. Scientometric map of coauthoring

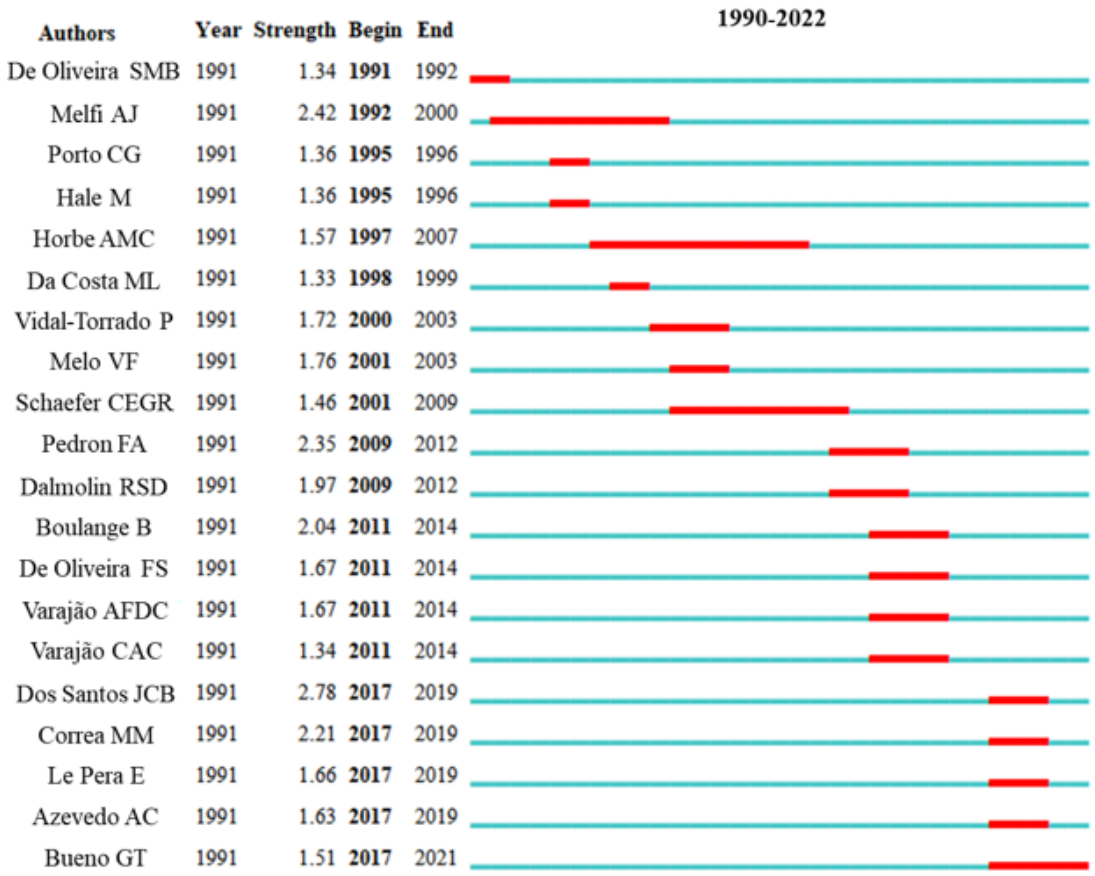


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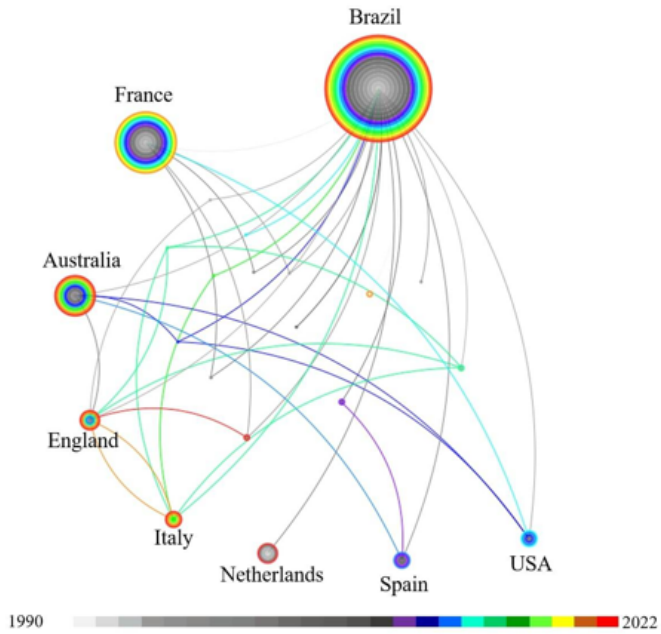
Figure 7. Top 20 authors and their citation bursts

Table 1. Main articles ordered by number of citations, according to ResearchGate

Ranking	Articles	Journal	Authors/Year	Citations	DOI
1	Chemical and mineralogical properties of kaolinite-rich Brazilian soils	Soil Science Society of America Journal	Melo et al. (2001)	158	10.2136/sssaj2001.6541324x
2	Brazilian Latosols and their B horizon microstructure as long-term biotic constructs	Australian Journal of Soil Research	Schaefer (2001)	156	10.1071/SR00093
3	(U/Th)/He geochronology of goethite and the origin and evolution of cangas	Geochimica et Cosmochimica Acta	Monteiro et al. (2014)	98	10.1016/j.gca.2014.01.036
4	Spatial variability of soil hydraulic conductivity along a tropical rainforest catena	Geoderma	Sobieraj et al. (2002)	95	10.1016/S00167061(02)00122-2
5	Podzolization as a deferralitization process: A study of an Acrisol-Podzol sequence derived from Paleozoic sandstones in the northern upper Amazon Basin	European Journal of Soil Science	Nascimento et al. (2004)	88	10.1111/j.13652389.2004.00616x
6	Landslide initiation in saprolite and colluvium in southern Brazil: Field and laboratory observations	Geomorphology	Lacerda (2007)	88	10.1016/j.geomorph.2006.03.037
7	Effects of lime on permeability and compressibility of two tropical residual soils	Journal of Environmental Engineering	Galvão et al. (2004)	75	10.1061/(ASCE)0733 (2004)130:8(881)
8	Nickel isotope fractionation during tropical weathering of ultramafic rocks	Chemical Geology	Ratié et al. (2015)	75	10.1016/j.chemgeo.2015.02.039
9	Controlling factors of gullying in the Maracujá Catchment, southeastern Brazil	Earth Surface Processes	Bacellar et al. (2005)	75	10.1002/esp.1193
10	Lateritic nickel deposits of Brazil	Mineralium Deposita	Oliveira et al. (1992)	72	10.1007/BF00197099

on the accumulation of citations, because of the 10 most cited articles, only 2 were published after 2010.

Brazilian researchers collaborated in studies on saprolite with researchers from institutions in 22 countries. Figure 8 shows these collaborations, with an emphasis on the main countries.



(Color figure online). Source: CiteSpace - Own elaboration

Figure 8. Scientometric map of network collaboration with other countries

Within the period considered in this survey (1990-2022), the oldest international partnerships began in the 1990s with France, followed by Australia, the Netherlands, Spain and the USA. This can be attested through the link coming from the center of the node of each country. Figure 8 shows that researchers from Brazil are currently collaborating with Australia, England, Italy and the Netherlands (the outer ring in red indicates collaborative publications in 2022).

Figure 9A shows the most representative journals of the cocitation network, especially in the last three years. Here, each journal is represented by a node. These nodes are represented by a series of rings in different colors that represent the year of citation. Finally, their thickness is proportional to the number of citations in a given period. The color of the links connecting the nodes represents the year in which it was cited. Among the 8 journals highlighted below, 4 (Geoderma, Chem Geol, Geo Cosm AC and Soil Sci Soc AM J) were among the top 10 with the greatest number of citations between 1990 and 2022 (Table 1).

As shown in Figure 9, there are a wide variety of cocited journals involved in saprolite research. Those highlighted in the present diverse scopes, journals with an interdisciplinary nature (Catena, Soil Sci Soc AM J and Clay Miner), were cited with high frequency in the last three years, except for Clay Miner in 2022 (Figure 9B). The journals focused on publishing

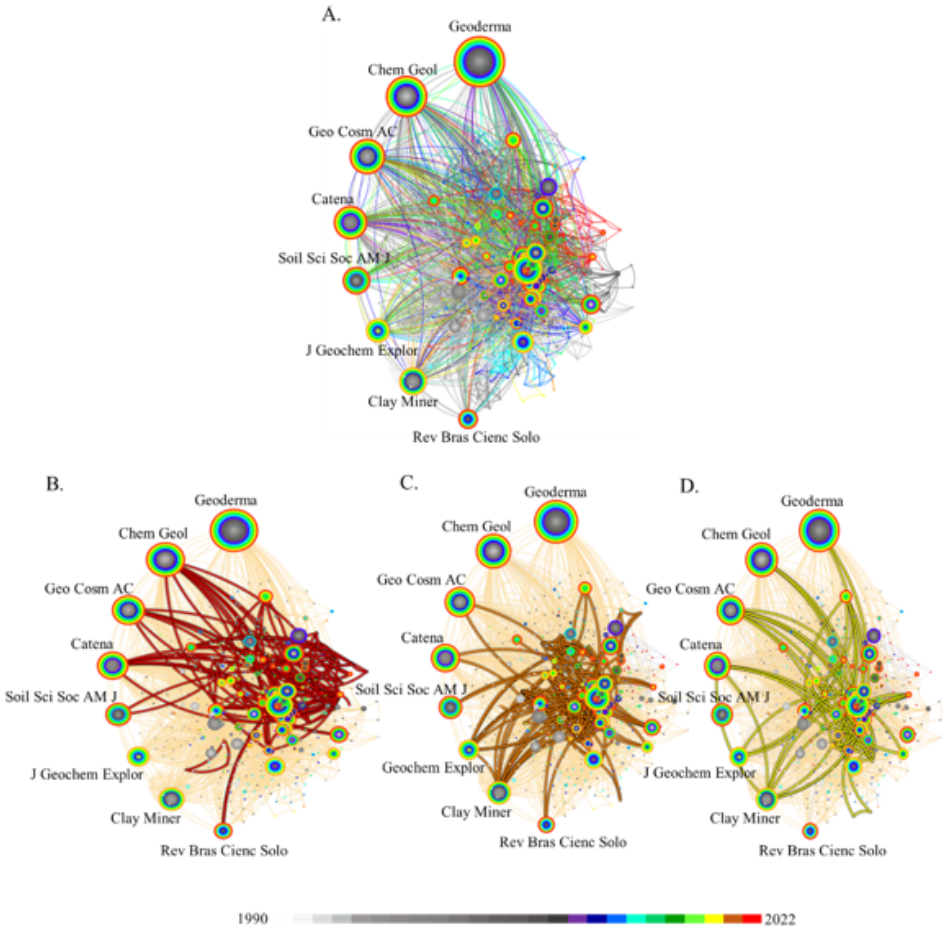


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Figure 9. (A) Scientific journals with the most-cited publications on saprolite (1990-2022); highlighting the years 2022 (B); 2021 (C) and 2020 (D)

research on soil science (Geoderma and Rev Bras Cienc Solo) showed a reduction in the number of citations in the last three years (Figure 9B and C - Geoderma; Figure 9D - Rev Bras Cienc Solo), despite the high citation numbers that Geoderma has accumulated in the last thirty-two years. The journals with a geochemical scope (Chem Geol, J Geochem Explor and Geo Cosm AC) had citations with varying frequencies.

Figure 10 is an overlay of maps of research articles on saprolite, isalterite, and isoalterite between 1990 and 2022. The overlay of maps detects the most productive disciplines that conduct focused research and the fundamental principles of this domain (Hu et al., 2022; Song et al., 2022). The nodes on the left represent the citing journals (knowledge carriers), and those on the right represent the cited ones (knowledge bases). The curve between two nodes indicates the relationship between the citations, and the strength of the curves (after the weight of the z score) is based on the number of citations (the thicker the line is, the greater the number of citations). In addition, the software builds ovals into the maps, which indicate clusters of highly active and cited journals. The size of these ovals is proportional to the number of publications that cite the cited journals (Chen & Leydesdorff, 2014).

The map overlay revealed that the papers with the key words "saprolite", "Isalterite" and "isoalterite" were mainly published in journals in the "Ecology, Earth, Marine" area (Figure 10). The connection curve (blue line) represents the papers that were cited in papers published in journals in the "Earth, Geology, Mathematical" and "Chemistry, Materials, Physics" areas. This can be interpreted as the "Ecology, Earth, Marine" area being the intellectual base for the other areas, with Z = 5,14. The Z index normalizes the citation frequency among different areas (Han et al., 2023). The Z value of this curve expresses a robust knowledge flow among these areas (Zhang et al., 2023).

The ovals highlighted on the right side of Figure 10 show the same sequence as the scientific journals shown in Figure 9. Based on these findings, the research area for this topic is interdisciplinary in character, owing to the varied scopes of the journals in which the path is inserted. In addition, despite knowledge areas such as "Economics, Political", "Psychology, Education", "Dermatology, Dentistry" and "Molecular, Biology" cited in journals from "Ecology, Earth, Marine", they did not have a score in the Z index.

The present study also identified the most cited keywords in articles about saprolite (Figure 11). Keywords carry the

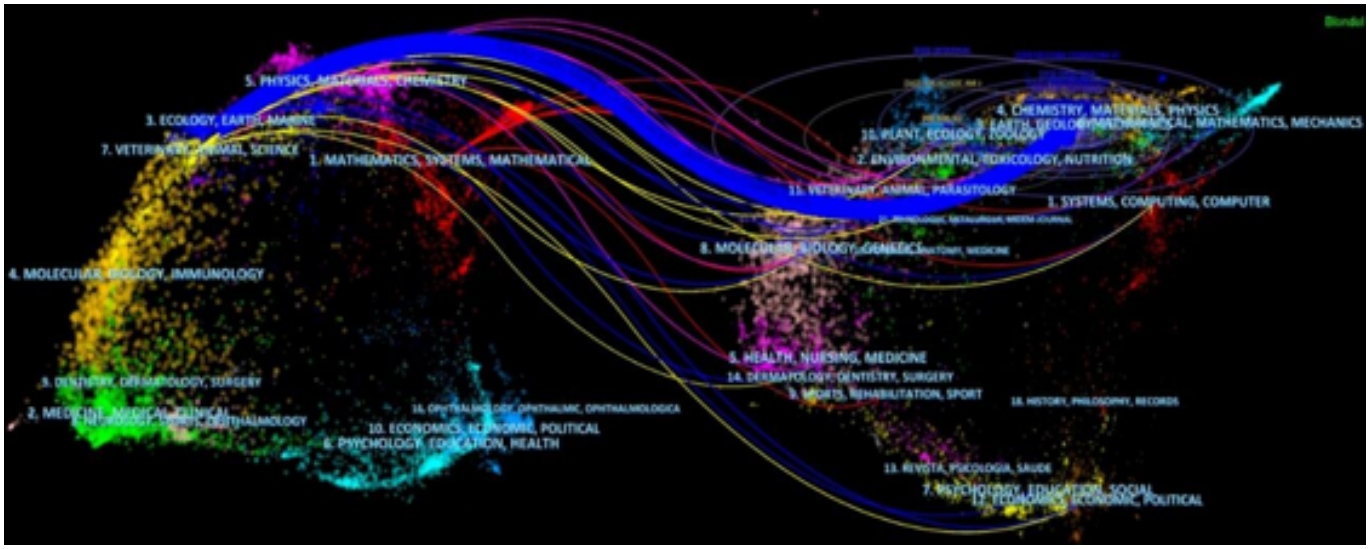

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Figure 10. Overlay of double maps on saprolite, isalterite and isoalterite

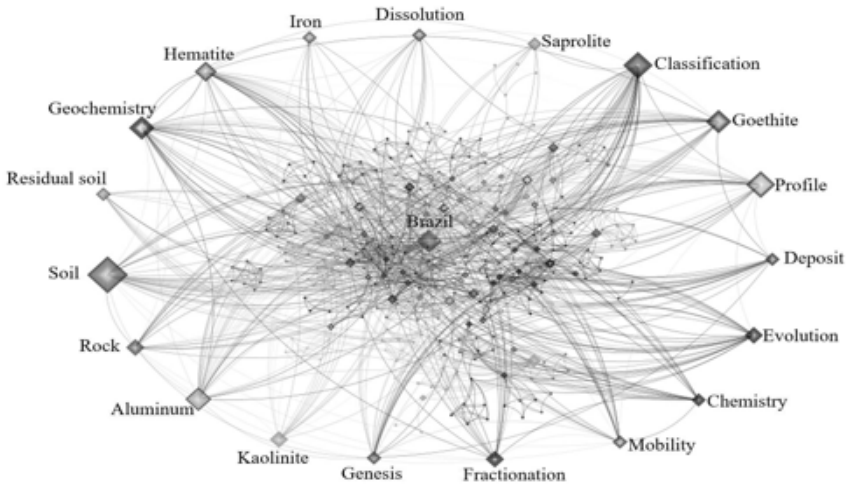

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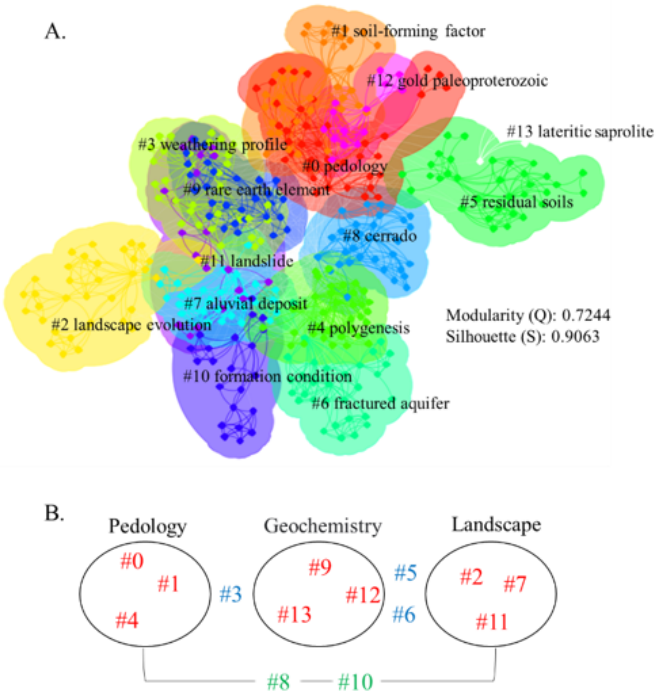
Figure 11. Keywords most commonly used in publications related to studying saprolite

most important and central information in the literature and are crucial to understanding the development trends of a given research field (Ma et al., 2022). CiteSpace was used to analyze such keywords and to identify trends and perspectives of present and future research (Chen, 2004). The size of the octahedron is proportional to the number of occurrences, and the connection between the octahedrons reflects the co-occurrence force between the keywords.

The 20 keywords used in this study are highlighted. The word 'Brazil', which symbolizes the advancement of saprolite studies in the Brazilian territory, appears in the center of the figure. A comparison of the words "Soil and Saprolite" revealed a greater occurrence of the first term and a lower occurrence of the second term. This same survey was carried out by Silva et al. (2022) on a global scale, where the same terminologies appeared with the same frequency number. The higher frequency of the word "soil" can be associated with the authors' concept of whether saprolite is part of the soil. In Brazil, several researchers prefer to use the term "soil", which encompasses the saprolite zone. Although the definition of saprolite is fairly narrow (rock altered in situ with little or no volume variation), its pedological nature depends on the soil definition adopted.

Another word that comes up frequently is "Classification." In Brazil, there is still no specific classification system for saprolite (Santos et al., 2018). This highlights the growing interest of Brazilian researchers in the development of a system for classifying the saprolite zone. The word "Rock" also appears in the list of words most frequently cited. This term is linked to the study of the source material, as shown in Figure 8, and may indicate the significant participation of geologists in studies involving saprolite. "Geochemistry", "Evolution", "Hematite", "Goethite", "Genesis" and "Profile" also appear more frequently, suggesting that the relationships between the sections at different depths in the regolith are of great interest to Brazilian researchers, especially in terms of their mineralogical aspects. This may suggest that publications on saprolite are more related to geological issues and weathering/pedogenic evolution of the regolith and less related to its geotechnical properties, for example.

To better understand saprolite studies, we combined keyword analysis with clustering (Figure 12A). A silhouette of S = 0.9063 was obtained, indicating that it is highly homogeneous since the closer to one the association of the keywords of each cluster is, the stronger the association. The modularity (Q = 0.7244) indicates good clustering quality throughout the network. The term "weathering profile" also appears in the cluster analysis and can be associated with studies on "lateriticsaprolite" (Negrão & Costa, 2021), which in turn is associated with "rare earth element" that are used as indicators of weathering processes (Faria Júnior et al., 2018; Ferreira et al., 2021), in addition to contributing to the search for the economically important minerals "gold-paleoproterozoic" (Varajão et al., 2020). The following terms were also found: "fractured aquifer", which is linked to the boundary of the saprolitic zone (NRC, 2001), and "cerrado", which is the biome with the largest number of studies on saprolite, based on the mapping performed by the state (Figure 3).



Research groups according to the authors. (Color figure online). Source: CiteSpace - Own elaboration

Figure 12. (A) Grouping of keywords for saprolite studies (differentiated by color) provided by CiteSpace. (B) Interpretation by the authors of the research groups

Other terms that appeared were "alluvial deposit" and "landscape", which are related to the transport of "allochthonous" material, which may imply the configuration of "landscape evolution". The term "residual soil", on the other hand, is associated with the material that remained in the place of origin. "Formation condition", "soil-forming factor", "polygenesis" and "pedology" are also subjects associated with studies on saprolithology (Santos et al., 2022a).

Based on the terms that were presented in the cluster analysis, the main saprolite research was centered on three groups "Pedology", "Geochemistry" and "Landscape" (Figure 12B). The symbols highlighted in red are topics related to the group. The topics in blue are closely linked between groups, and the topics in green present an intricate link between "Pedology and Landscape". Through this analysis, it was possible to visualize the main topics studied in the context of saprolithology and which topics have not yet been addressed.

Therefore, keywords involving the physical parameters of soil, microbiological and climate change did not appear to be the most cited. This may be due to the absence of well-established methods, the difficulty of accessing these materials or the time window considered for this paper since older studies generally focused on the geochemical and mineralogical aspects of saprolite. As a result, studies involving these subjects continue to merit consideration, as this approach is currently underutilized.

Conclusions

1. The number of articles published on saprolit*/isalterit*/isoalterit* shows an increasing trend during the period of 1992-2022.

2. Brazil has the largest silicate carbon sink (SCS) area in the world. In particular, the Amazon River and Paraná River Basins (24.41% of the global silicate carbon sink) have received little attention in saprolite research, especially the Amazon River Basin.

3. Most studies on saprolite have been developed by researchers from federal and state institutes. These researchers play an important role in networking with foreign researchers.

4. Research on saprolite has interdisciplinary characteristics, covering areas such as pedology, geology and geography.

5. Considering the number of articles published by study location, more articles were published on saprolite in the southeastern region than in the other regions of Brazil (98 of 193 locations; 50.77%). The ratio of articles-research-state to articles-author-state confirms the strong partnership that exists between researchers from several institutions in Brazil.

6. Brazilian saprolite papers were published mainly in the "Ecology, Earth, Marine" area and were cited by various other knowledge areas.

7. Keyword co-occurrence, cluster analysis, and group analysis indicated that the search hot key words in this field are "Soil," "Classification," "Profile," "Geochemistry," and "Goethite" and "Hematite". There is a lack of studies involving issues related to water dynamics, carbon dynamics, and microbial life in regolith/saprolite.

8. The saprolite geographical research frontier is the Amazon River Basin, and the methodological frontier is the study of water, carbon and microbial life.

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