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ORIGINAL PAPER

Soil Remineralizers: Advances in Scientific Production Following the Establishment of Legal Frameworks in Brazil

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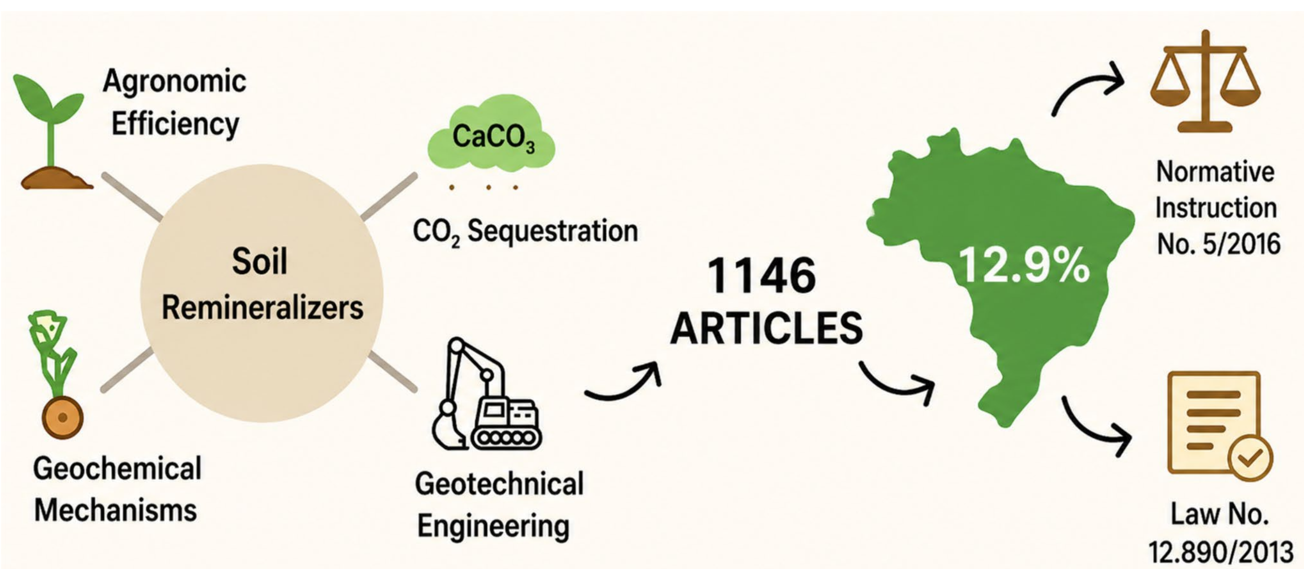
Abstract
Brazil's growing dependence on imported fertilizers and the environmental impacts associated with their use have driven the search for sustainable alternatives, among which soil remineralizers (REMs), commonly known as rock powders, stand out. This study provides a global and national bibliometric overview of the dissemination of REMs studies between 2006 and 2025. Based on a bibliometric dataset comprising 1,146 articles indexed in the Web of Science and Scopus databases, the analysis was conducted using VOSviewer and Bibliometrix (RStudio). The results indicate that China leads global publication output on REMs (21.1%), followed by Brazil (12.9%) and the United States (10.9%). In the Brazilian context, strong growth was observed following the regulatory milestones established by Law No. 12,890/2013 and Normative Instruction No. 5/2016. Research on REMs has evolved significantly over the past two decades, transitioning from conceptual approaches to practical applications in agricultural systems, and has been structured around four main themes: agronomic efficiency, CO_2 sequestration, geochemical mechanisms, and the use of rock powder in geotechnical engineering. In conclusion, REMs represent a low-cost and sustainable strategy capable of reducing dependence on conventional inputs, improving the fertility of tropical soils, and contributing to climate change mitigation. Moreover, we found that the Brazilian experience with REMs may be a replicable model for other countries seeking to reduce their vulnerability to the fertilizer market and to promote low-carbon agricultural practices. Expanding research in underexplored regions and monitoring toxic elements remain future challenges for consolidating the large-scale use of REMs.

Graphical Abstract



Keywords Rock powder · Alternative fertilizers · Bibliometrics · Global research trends · Policy

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1 Introduction

Brazil is one of the world's leading food producers, with grain production alone estimated at 353.4 million tons in the 2025/26 crop season (CONAB, 2025). However, the country's dependence on imported fertilizers represents a major vulnerability for the national agricultural sector, especially in the current context of geopolitical and economic instability in the international market. In 2025, approximately 88.21% of fertilizers containing nitrogen (N), phosphorus (P), and potassium (K) formulations delivered to the Brazilian market were imported (ANDA, 2026).

This scenario has been aggravated by the sharp rise in the price of agricultural inputs since 2022, triggered by the onset of the Russia–Ukraine conflict, as both countries are major fertilizer exporters to Brazil. According to Zhang et al. (2023), the instability in the supply of agricultural inputs from Eastern Europe affected 136 countries and territories, with the most significant impacts observed in Estonia, Mongolia, Kazakhstan, Brazil, the United States, China, and India.

From an environmental standpoint, the intensive use of soluble chemical fertilizers results in several negative impacts, including soil chemical degradation, contamination of surface and groundwater, and increased greenhouse gas emissions, particularly N_2O (Elamiri et al. 2025; Priya et al. 2024). Chemical soil degradation involves processes such as acidification, salinization, reduction of cation exchange capacity (CEC), and accumulation of toxic compounds, phenomena consistently observed in systems highly dependent on soluble fertilizers (Lal 2015).

In recent decades, the development of alternative slow-release fertilizers capable of supplying crop nutrition while reducing environmental impacts has intensified. However, there remains an urgent need for public policies that promote the adoption of more sustainable agricultural practices (Krein et al. 2023), which should align with the United Nations Agenda 2030, particularly with "Sustainable Development Goal 2.4", aimed at fostering resilient production systems with greater productivity and reduced ecosystem impacts (UN, 2015).

Among alternative fertilizers are soil remineralizers (REMs), commonly referred to as rock powders, which are applied in agriculture through a technique known as rock remineralization or stonemeal (Swoboda et al. 2022). This is a low-cost technique that enables high productivity in the medium and long term (Ramos et al. 2014), with minimal negative environmental impact, despite certain limitations related to the immediate release of nutrients. Nonetheless, the development of REMs inoculated with solubilizing microorganisms is a promising alternative. For instance, Assunção et al. (2024) reported interactions between melilite olivine and rhizobacteria *Bacillus subtilis* and *Bacillus megaterium*, which enhanced the availability of K and calcium (Ca) in the soil over an eight-month period.

Rocks used for soil remineralization are mostly by-products of mining activities targeting other resources, such as those used in civil construction, gemstones, and ornamental stones. Over the past two decades, the use of mining residues for agricultural purposes has gained legal recognition in Brazil. The country presents favorable conditions for the application of soil remineralization techniques, including a rich geodiversity associated with tropical and subtropical climates that accelerate weathering processes, especially hydrolysis.

From a regulatory perspective, Brazil is one of the few countries to have established specific legislation governing the use of REMs in agriculture. In this context, the country amended Law No. 6,894/1980, commonly known as the Fertilizer Law, through Law No. 12,890/2013, which incorporated REMs as a category of agricultural inputs. Subsequently, in 2016, the Brazilian Ministry of Agriculture, Livestock, and Supply (MAPA) issued Normative Instruction No. 5 (IN 5/2016), regulating the commercialization of rock powders as agricultural inputs by establishing minimum specifications and guarantees. Among these requirements, the sum of bases ($CaO + MgO + K_2O$) must be $\geq 9\%$, K_2O content must be $\geq 1\%$, free silica (SiO_2) content must not exceed 25%, and the limits for potentially toxic elements are 15 ppm for arsenic (As), 10 ppm for cadmium (Cd), 0.1 ppm for mercury (Hg), and 200 ppm for lead (Pb) (Brasil 2016).

Compliance with the requirements of IN 5/2016, combined with Brazil's vast variety of lithologies, has coincided with increased scientific interest in the geochemical properties of rocks suitable for this purpose, including basalts and andesites (Cardozo et al. 2024a, b; Medeiros et al. 2021), oil shale (Martinazzo et al. 2020), rhythmites (Rodrigues et al. 2021), and gneisses (Medeiros et al. 2023). However, a research gap still exists regarding a comprehensive national and global scientific overview of REMs, considering their growing adoption as a sustainable agricultural practice over the past two decades.

Given the above considerations, this study aims to provide a bibliometric overview of REMs at both national and global scales. The central premise is that the expansion of scientific production in Brazil is consistent with the timing of key regulatory milestones related to REMs, beyond their role in promoting the registration and adoption of these materials in agriculture. To examine this temporal relationship, the study focuses on a twenty-year period (2006–2025) encompassing the enactment of Law No. 12,890/2013 and the publication of IN 5/2016 by MAPA. This research seeks to contribute to the advancement of soil remineralization techniques by identifying existing gaps and opportunities for future studies.

2 Methods

The methodological design was based on Guo et al. (2023), combining bibliometric techniques and science mapping. The primary data source was the Web of Science (WoS, Clarivate Analytics), specifically the Core Collection (SCI-Expanded, SSCI, and ESCI), due to its rigorous indexing standards and widespread use in bibliometric studies. To expand literature coverage and assess the robustness of the observed patterns, Scopus (Elsevier) was used as a complementary database.

The search strategy was designed to capture the diversity of terminology used in the field of soil remineralization. The following query was applied using the Topic Search (TS) field in the Web of Science (WoS), which includes title, abstract, author keywords, and Keywords Plus: TS = ("soil") AND ("rock powder" OR "rock dust" OR "stone meal" OR stonemeal OR "soil remineralization" OR "remineralization" OR agromineral* OR "silicate rock*" OR "rock-based fertilizer*" OR "ground basalt" OR "crushed rock" OR "rock amendment*" OR "enhanced weathering").

An equivalent query was adapted and applied in the Scopus database using the TITLE-ABS-KEY field. The search was conducted on April 22, 2026. The results were limited to peer-reviewed original articles, published between 2006 and 2025, and written in English. The analysis was restricted to English-language articles to ensure consistency in metadata standardization and comparability across databases, although this may have reduced the representation of regional literature published in other languages. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) inspired flow diagram was used to describe the identification and screening process. The initial search retrieved 1308 records from Scopus and 1221 from WoS. After applying filters for publication year, document type, and language, the final datasets included 953 and 855 records, respectively. Despite differences in database coverage, the main temporal trends and thematic structures were consistent across both datasets, supporting the robustness of the analysis. Duplicate records were removed using the bibliometrix R package, resulting in a final dataset comprising 1,146 records (Fig. 1; Online Resource 1).

The full records and cited references of these articles were exported in a format compatible with bibliometric analysis software such as VOSviewer (Visualizing Scientific Landscapes), developed by Van Eck and Waltman (2010). VOSviewer enables the identification of co-occurrence and clustering of bibliometric variables through visual maps in which items are represented by labels. Keyword co-occurrence analysis was based on a combined set of author keywords and indexed keywords (Keywords Plus in WoS and indexed keywords in Scopus), using fractional counting and association strength normalization.

In this study, three keyword co-occurrence maps were generated using different frequency thresholds (15, 25, and 35 occurrences) to explore the thematic structure of the field at different levels of granularity. Lower thresholds were used to capture a broader set of emerging and secondary topics, while higher thresholds were applied to identify the most established and central research themes. Although all three levels were used to support the exploratory analysis, the interpretation of research clusters was based primarily on the most restrictive threshold (≥35 occurrences). This decision was made to ensure higher thematic stability, reduce noise, and to highlight the core intellectual structure of the field.

To improve the clarity of the analysis, a thesaurus file was created and applied in VOSviewer to merge synonyms and standardize variations in keyword spelling (e.g., "rock dust", "rock powder", and "stonemeal"). Generic and non-informative terms (e.g., "study" and "effect") were

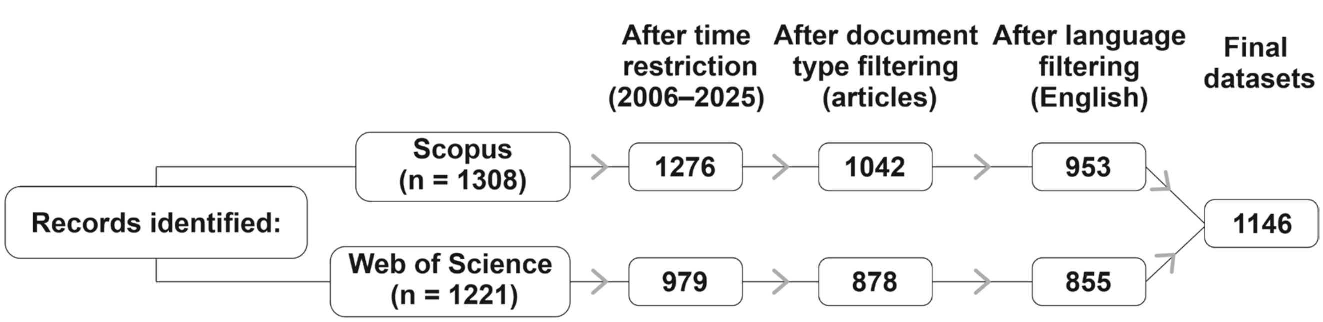


Fig. 1 Preferred reporting items for systematic reviews and meta-analyses. (PRISMA)-inspired flow diagram illustrating the identification, screening, and inclusion of records retrieved from the Web of Science and Scopus databases. The diagram shows the number of records at each stage after applying filters for publication year (2006–2025), document type (articles), and language (English)

excluded. The colors represent clusters of items with similar characteristics, automatically calculated by the program, and the distance between items indicates the strength of the relationships among them. To determine the average annual growth rate, the mean number of citations per document, and to identify articles produced through international collaborations, the Bibliometrix package from the R platform was used.

3 Results and Discussion

3.1 Geographical and Temporal Analysis of the use of REMs worldwide and in Brazil

Within the period analyzed, the study field showed an annual growth rate of 8.19%. The average of 30.21 citations per article demonstrates the relevance and recognition of these publications within the academic community. Among the analyzed documents, 25.51% resulted from international collaborations, suggesting significant integration among researchers from different countries, which enhances knowledge exchange and increases the global impact of research (Fig. 2). Regarding the authors' institutional affiliations across the dataset, China leads the global ranking of studies focused on understanding the mechanisms of action and potential applications of REMs, accounting for 21.1% of the publications, followed by Brazil (12.9%), the United States (10.9%), and the United Kingdom (6.5%).

Scientific collaboration indicators are essential for assessing patterns of internationalization in research output. Overall, a clear predominance of Single Country Publications (SCP) over Multiple Country Publications (MCP) is observed, indicating that most scientific production is still conducted at the national level. Regarding collaboration structure, China records 185 SCP and 57 MCP, while Brazil presents 125 SCP and 23 MCP. The United States shows 96 SCP and 29 MCP, and the United Kingdom 51 SCP and 23 MCP. These findings suggest that, despite the predominance of nationally based publications across all countries, there are varying levels of integration into international research networks. Countries such as the United Kingdom demonstrate a higher degree of international collaboration, whereas Brazil and China show a stronger concentration of nationally produced publications, albeit with substantial overall scientific output (Fig. 2a).

In terms of overall country participation across the 1,146 analyzed publications, China leads with 921 occurrences, followed by the United States (556), Brazil (524), and the United Kingdom (280). This indicator reflects the frequency of country appearances in author affiliations, capturing their level of integration within collaborative research networks. The results suggest a scientific landscape in which China plays a central role, while Brazil demonstrates a strong presence in global co-authorship networks, with a magnitude comparable to that of major scientific powers (Fig. 2b).

Considering the Brazilian scenario over the last two decades, the Brazil is a pioneer in REMs technique, an average annual growth rate of 7.91% can be observed, with a mean of 15.59 citations per document (Fig. 3), which compares global and Brazilian publication trends over a two-decade period, both showing a growing trajectory. The increasing interest in remineralization in Brazil is likely associated with several factors, including the country's rich geodiversity, climatic conditions that intensify weathering processes, its status as one of the world's largest importers of agricultural inputs, the potential reduction in production costs, and, importantly, the fact that Brazil is one of the few countries in the world with specific legislation and regulations governing the commercialization of REMs. At both global and national scales, an increase in the number of publications can be observed over time. However, at the national level, it is noteworthy that 81.03% of publications date from the period following the release of IN 5/2016. Considering the period from 2006 to 2016, the average annual growth rate of the field was 8.45%, whereas from 2017 to 2025 this value increased to 19.83%, indicating a substantial rise in scientific output.

This substantial rise in scientific output coincides with Brazil's growing dependence on imported fertilizers. In 2025, the import volume of intermediate and complex NPK-based fertilizers reached 43.33 million tons (ANDA, 2026), representing a 4.57% increase compared to the previous year. Between 2018 and 2024, NPK imports grew at an average annual rate of 7.51%. The fertilizers used in the country are predominantly sourced from Russia, China, Canada, Morocco, and Belarus, and are thus subject to foreign policies and exchange rate fluctuations (Brasil 2021).

As shown in Table 1, Science of the Total Environment, published by Elsevier, stands out as the leading journal on this topic, with 34 publications, followed by Cold Regions Science and Technology (28) and Applied Geochemistry (24). Other relevant journals include Frontiers in Climate and Geochimica et Cosmochimica Acta (20 each), Biogeosciences (18), Chemical Geology (17), Geoderma, Journal of Cleaner Production, and Pesquisa Agropecuária Brasileira (15 each), as well as Scientific Reports (12). This distribution can be attributed to the scope and thematic affinity of these journals.

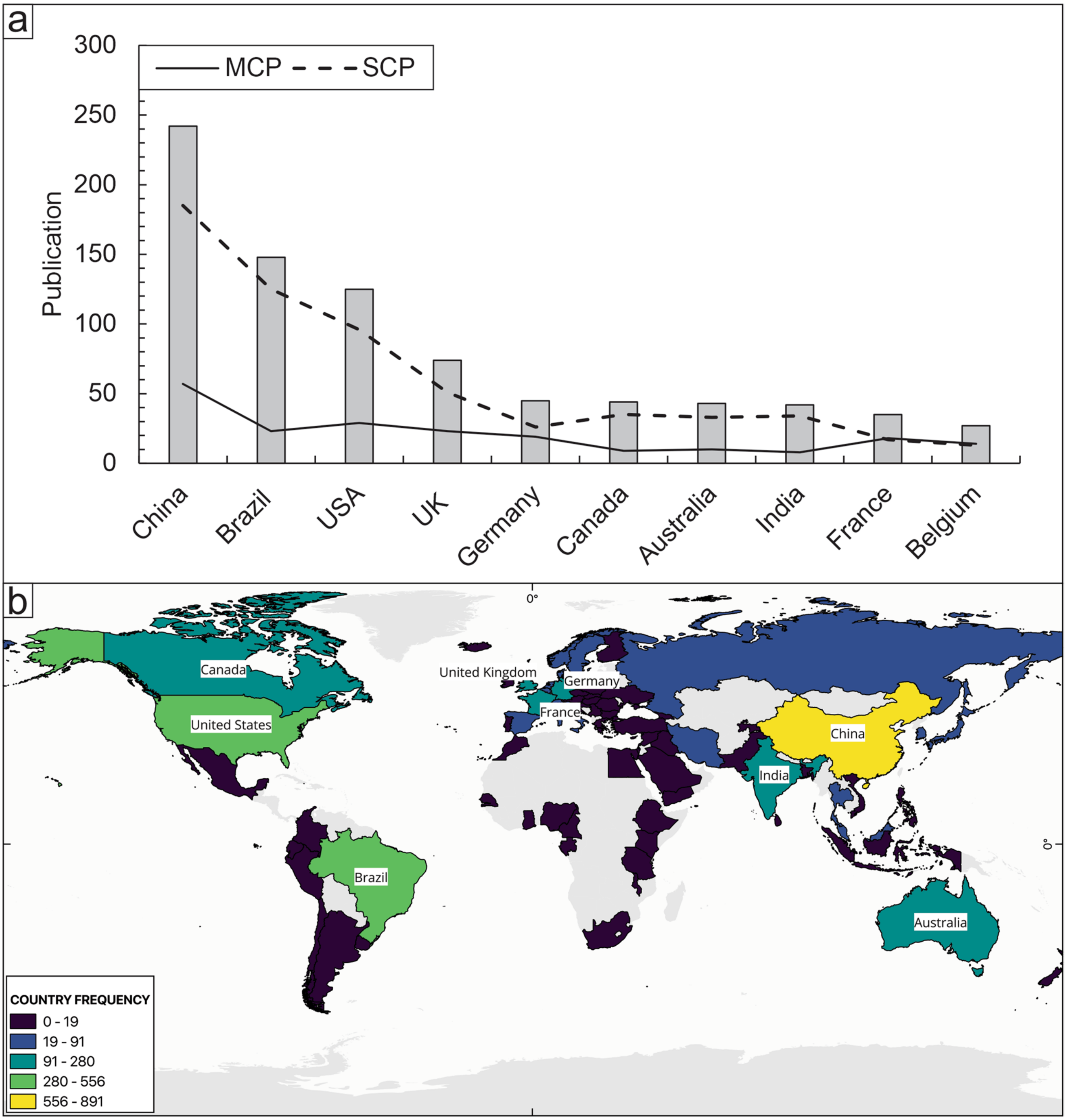


Fig. 2 (**a**) Percentage distribution of scientific publications on soil remineralizers (REMs) by country, including single country publications (SCP) and Multiple country publications (MCP). (**b**) Global distribution of country participation in scientific publications on soil remineralization, based on author affiliations. The color scale represents the frequency of country occurrence across publications

3.2 Co-occurrence Analysis of Keywords Related to REMs in Scientific Publications

The bibliometric keyword co-occurrence map represents the research field as a whole, highlighting the associations among different lines of investigation. The database used contains 10,369 keywords; due to this large number, three keyword co-occurrence maps were generated using different frequency thresholds in order to obtain a cluster structure with sufficient analytical clarity to enable the identification of patterns. The fractional counting method was adopted, and normalization was performed

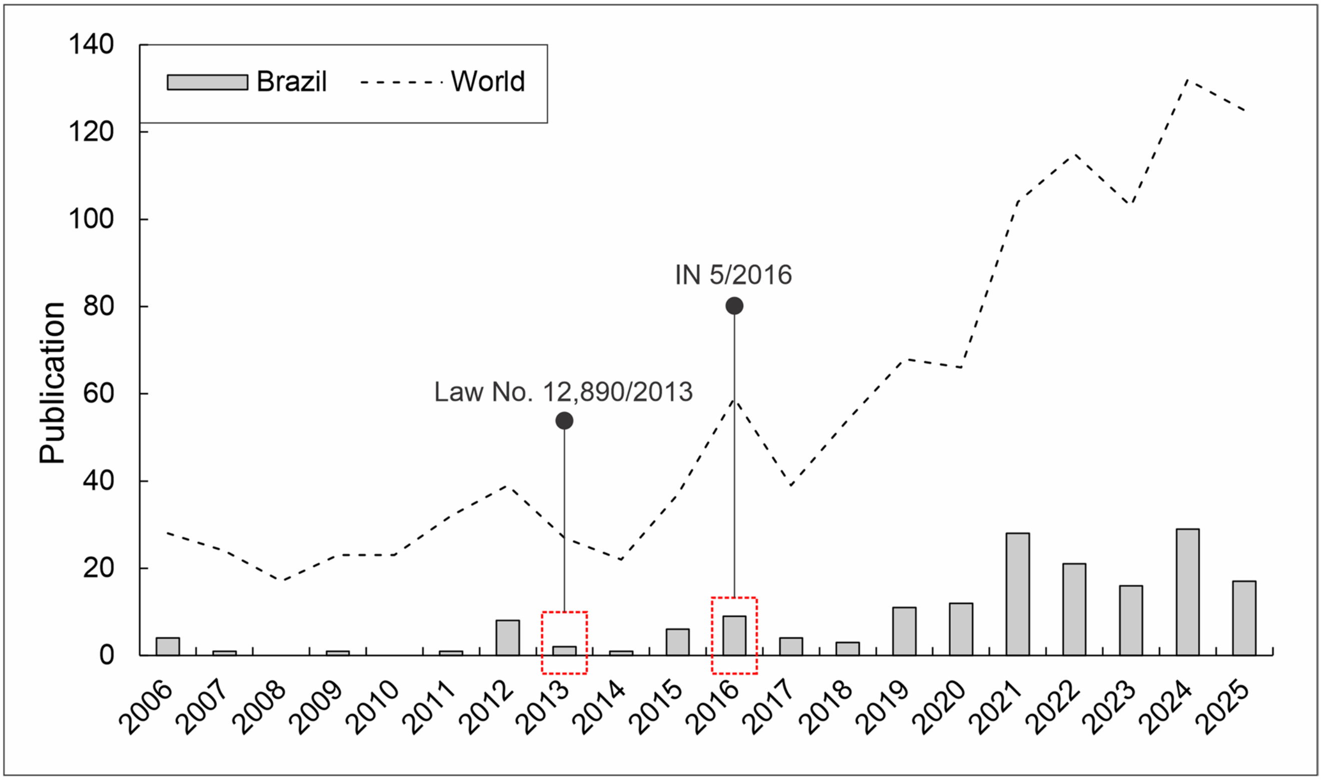


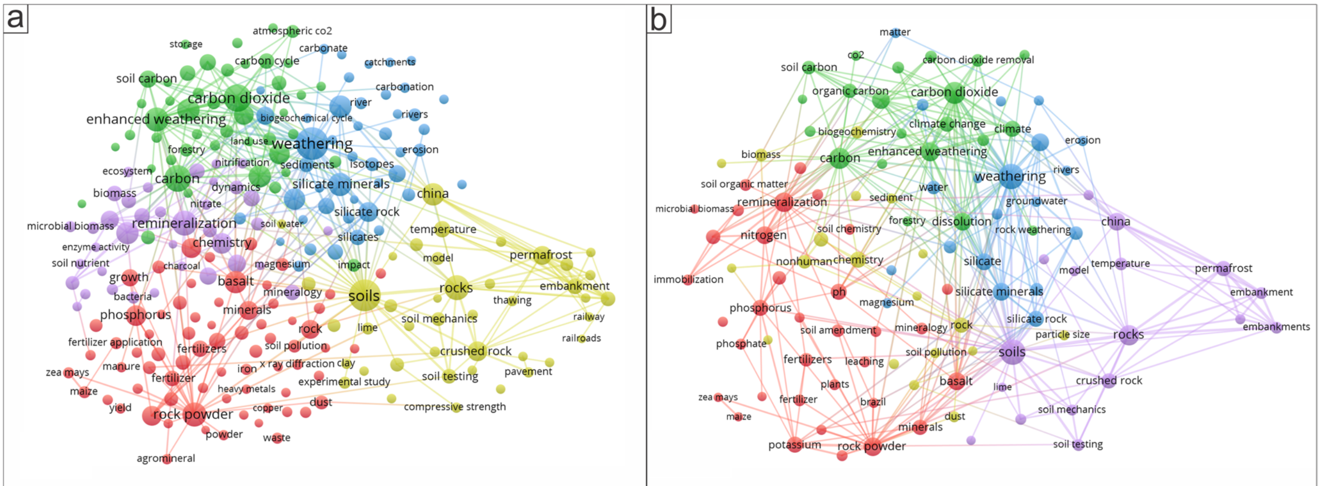
Fig. 3 Annual number of publications on soil remineralization between 2006 and 2025, at both global and Brazilian scales

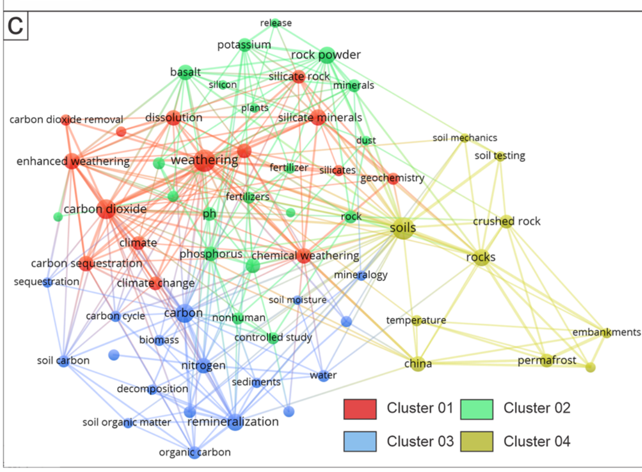
Table 1 Top twenty journals with the greatest number of publications on soil remineralizers (REMs)

N°	Journal	Publications	Percent (%)
1	Science of the Total Environment	34	2.97
2	Cold Regions Science And Technology	28	2.44
3	Applied Geochemistry	24	2.09
4	Frontiers in Climate	20	1.75
5	Geochimica et Cosmochimica Acta	20	1.75
6	Biogeosciences	18	1.57
7	Chemical Geology	17	1.48
8	Geoderma	15	1.31
9	Journal of Cleaner Production	15	1.31
10	Pesquisa Agropecuaria Brasileira	15	1.31
11	Scientific Reports	12	1.05
12	Environmental Earth Sciences	11	0.96
13	Global Change Biology	11	0.96
14	Catena	10	0.87
15	Environmental Research Letters	10	0.87
16	Environmental Science & Technology	10	0.87
17	Biogeochemistry	9	0.79
18	Communications In Soil Science And Plant Analysis	9	0.79
19	Journal Of Environmental Management	9	0.79
20	Transportation Geotechnics	9	0.79

using the association strength method. Minimum occurrence thresholds of 15, 25, and 35 were defined, resulting in networks composed of 240, 111, and 63 keywords, respectively, after applying a thesaurus file to merge synonymous terms and reduce redundancies. Network visualization was generated using the software's default parameters, including random starts (1), maximum iterations (1000), initial step size (1), step size reduction (0.75) and step size convergence (0.001). The map composed of 63 keywords was selected for analysis, as it presented a cluster structure with greater analytical clarity, enabling the identification of patterns. The other maps resulted in overly dense networks, with a large number of weakly connected terms (Fig. 4a-c).

Cluster 1 (red) includes terms such as carbon dioxide, carbon dioxide removal, carbon sequestration, chemical weathering, climate, climate change, dissolution and enhanced weathering, which refer to methodologies and initiatives aimed at enhancing the capture of atmospheric CO_2 through a mechanism known as enhanced weathering. Beyond the bibliometric corpus, complementary experimental and geochemical studies help to explain the processes represented in this thematic cluster. In its final stage, this process encompasses the geochemical reaction





Cluster 1	carbon dioxide, carbon dioxide removal, carbon sequestration, chemical weathering, climate, climate change, dissolution, enhanced weathering, geochemistry, rates, silicate, silicate minerals, silicate rock, silicates, weathering
Cluster 2	basalt, biochar, chemistry, controlled study, dust, fertilizer, fertilizers, growth, leaching, minerals, nonhuman, ph, phosphorus, plants, potassium, release, rock, rock powder, silicon, soil amendment
Cluster 3	biogeochemistry, biomass, carbon, carbon cycle, concentration (composite), decomposition, mineralization, mineralogy, nitrogen, organic carbon, organic-matter, remineralization, sediments, sequestration, soil carbon, soil moisture, soil organic matter, water
Cluster 4	china, crushed rock, embankment, embankments, permafrost, rocks, soil mechanics, soil testing, soils, temperature

Fig. 4 Keyword co-occurrence maps generated using different minimum occurrence thresholds: (**a**) 15 occurrences; (**b**) 25 occurrences; and (c) 35 occurrences. The colors represent thematic cluster identified in each network. The table summarizes the main terms associated with each cluster in the most restrictive threshold (≥35 occurrences)

of mineral carbonation, in which atmospheric CO_2 reacts with silicate minerals such as olivine, pyroxene, serpentine, and K feldspar, forming stable carbonates and thus promoting long-term carbon sequestration (Renforth & Henderson, 2017). Kelland et al. (2020) and Cample et al. (2022) estimate that a single application of basalt powder can achieve carbon sequestration rates ranging from 2 to 4 t CO_2 ha^{-1} over a period of up to five years. Conversely, Medeiros et al. (2023) emphasize that the magnitude of this capture is relatively small when compared to other negative emission strategies, such as the adoption of conservation tillage practices. However, these practices are not necessarily competitive, but possibly synergic.

The second cluster (green) includes keywords such as basalt, dust, fertilizer, fertilizers, growth, leaching, ph, phosphorus, plants, potassium, release, rock, rock powder, silicon and soil amendment, focusing on the agronomic efficiency of REMs and their direct impact on crop productivity. As contextual evidence from the broader agronomic literature, experimental studies have reported positive effects of REMs application on crop yield, nutrient availability, and soil chemical properties under different environmental conditions. Such effects have already been observed in different Brazilian regions. In southeastern Brazil, Rodrigues et al. (2024) reported that the application of 2,500 kg ha^{-1} of basalt powder in tropical soils increased soybean and sorghum yield by 15% and 35%, respectively. The authors also highlighted beneficial effects on soil health following REMs application, such as increases in P, sulfur, Ca, K, and magnesium (Mg) contents, CEC, and base saturation at the 0.00–0.20 m soil layer. When compared with conventional fertilization, Rodrigues et al. (2025) observed that the use of pyroxenite delivered statistically similar tomato yield. Moreover, the authors found that this REMs treatment promoted Si accumulation in leaves, which may represent a secondary agronomic benefit, particularly by enhancing tolerance to abiotic stress.

The third cluster (blue), groups the terms decomposition, mineralization, mineralogy, nitrogen, organic carbon, organic-matter, remineralization, sediments, soil carbon and soil moisture, encompassing studies aimed at understanding the physicochemical properties of minerals and the mechanisms associated with rock powder dissolution and nutrient release. Beyond the bibliometric patterns, experimental and laboratory studies provide mechanistic evidence for the processes represented in this cluster. The bioweathering process promoted by root activity is essential for REMs efficiency, as it is the primary mechanism responsible for mineralogical transformation on an agronomic timescale. Laboratory studies support this premise. According to Krahl (2020), the contact between rock powder and water, in the absence of roots, does not induce detectable mineralogical changes. Conversely, nutrient availability tests using 2% citric acid to simulate natural soil conditions in volcanic rocks have shown to promote the release of micro- and macronutrients, particularly Ca, K, and Mg, detected in the leachate (Cardozo et al. 2024a, b; Ramos et al. 2015). Fine particle size is also a key factor for the effectiveness of REMs, as smaller particles have a larger specific surface area, enhancing weathering action. Fractions <0.053 mm and between 0.053 and 0.3 mm promote the increase of CEC, whereas fractions >0.3 mm exhibit less significant changes (Martins et al. 2023).

The dissolution rate of minerals reflects their susceptibility to weathering, allowing classification into groups of high, medium, or low solubility. Highly weatherable minerals such as chlorides, sulfates, carbonates, phosphates, nepheline, volcanic glass, and micas (biotite and phlogopite) are often used in fertilizers and soil amendments and are generally associated with sedimentary and metamorphic rocks such as phosphorite and marble, which occur in specific localities. Minerals with moderate dissolution rates such as feldspars, zeolites, olivine, calcic and sodic plagioclase, pyroxenes, amphiboles, epidotes, and micas (glauconite) are commonly used as REMs due to their predominant occurrence in mafic igneous rocks and, to a lesser extent, in metamorphic rocks. Minerals with low weathering susceptibility such as K feldspar, mica (muscovite), phyllosilicates, clay minerals, and hydroxides (e.g., gibbsite and goethite), in addition to quartz, have more stable crystal structures and are less suitable for use as REMs. These minerals make up a large proportion of felsic igneous and metamorphic rocks such as granite, quartzite, and gneiss, and are also the main components of the soil's mineral fraction (Corrêa & Oliveira, 2024).

The fourth cluster (yellow) does not show a direct relationship with agronomic purposes unlike the other clusters; instead, it includes prominent terms such as China (84 occurrences), permafrost (56 occurrences), crushed rock (54 occurrences), embankments (38 occurrences), and soil mechanics (36 occurrences). This cluster represents a substantial and distinct thematic branch within the expanded search strategy, capturing the geotechnical and engineering applications of rock-derived materials, particularly for soil stabilization and permafrost protection. For instance, engineering studies have demonstrated that crushed-rock embankments on the Qinghai–Tibet Plateau enhance convective air cooling and mitigate permafrost degradation (Mei et al. 2021). Retaining this cluster is vital as it highlights a major global research front led by Chinese institutions regarding alternative uses of crushed stone. A sensitivity analysis confirmed that while this engineering literature forms a robust and highly connected sub-network, its conceptual boundaries remain peripheral to the core agricultural remineralizer literature, meaning its inclusion does not distort or alter the country rankings, journal distributions, or thematic conclusions regarding agronomic REM applications.

3.3 Temporal Dynamics of Keywords in the Scientific Literature on REMs

The map presented in Fig. 5 refers to the period of highest occurrence of each analyzed term, revealing research trends on REMs over the last decade (2016–2025). Only this period was analyzed, as the previous years did not show a significant frequency of publications, making the most recent decade representative of current trends. In the first half, from 2016 to 2020, theoretical and conceptual studies predominated, focusing on understanding the weathering processes acting on rock dust and enabling the release of nutrients into the soil.

In the second half of the period, from 2021 to 2025, practical studies with crops and comparative analyses between conventional fertilization methods, REMs, and combinations with chemical fertilizers, organic compounds, and more than one type of REMs stand out. For example, in the comparison of the benefits of applying limestone and basalt powder in soybean and corn crops, basalt powder promoted an increase in the dry matter content of the aerial parts of the plants, along with higher Ca, Mg, and P levels (Luchese et al. 2023). In the last three years (2023, 2024 and 2025) the terms enhanced weathering and carbon dioxide removal have gained prominence, reflecting the enhancement of the secondary effect of REMs for atmospheric CO_2 sequestration, contributing to mitigating the impacts of the climate crisis.

3.4 Integrative Analysis and Perspectives on the use of Remineralizers in Brazil

The last two decades have been fundamental for the dissemination of the use of REMs in Brazil, resulting from

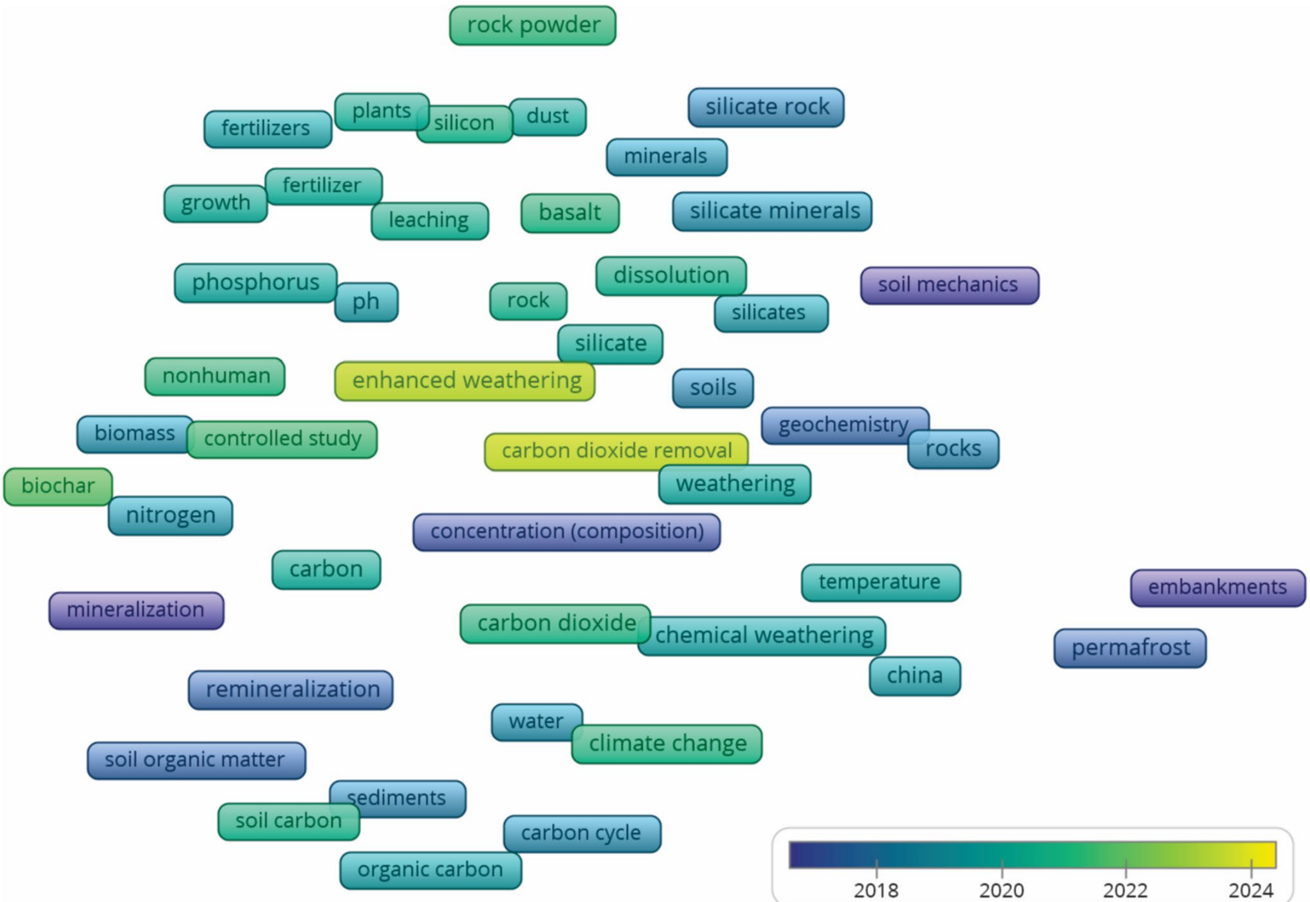


Fig. 5 Temporal overlay visualization of keyword co-occurrence based on terms with a minimum occurrence threshold of ≥35. Colors represent the average publication year of each term, ranging from earlier topics (blue) to more recent topics (yellow)

both public and private efforts, especially the partnership between governmental institutions (universities and research institutes) and companies in the mining sector. According to the Brazilian Association of Producers of Soil Remineralizers and Natural Fertilizers (ABREFEN), in 2024 Brazil had 58 REMs registered at the MAPA, while according to Integrated System of Agricultural Products and Establishments (SIPEAGRO), the system used by MAPA for the registration and certification of agricultural establishments and products, by 2025 the number of registered REMs had reached 72 (Table 2).

The production of REMs and similar products based on silicate rock in 2023 ranged between 1.5 and 1.6 million tons, concentrated in the southern and southeastern regions of the country, as shown in Fig. 6. On the other hand, the northern and northeastern regions of Brazil still lack studies that could lead to products eligible for registration with MAPA, as shown in Table 3.

Ferreira et al. (2025) analyzed the potential of granite outcrops in the northeastern region of the state of Pará and found limitations due to the high content of free SiO_2 (46.5%). However, the material stood out for its high K_2O content (6.02%), proving to be promising for combined use with other lithologies that have low Pb contents. In a global context, the dissemination of alternative fertilizers

Table 2 Number of registered Soil Remineralizers (REMs) in Brazil from 2018 to 2025

Year of registration	Number of registered REMs
2018	2
2019	3
2020	5
2021	8
2022	18
2023	14
2024	10
2025	12
Total	**72**

Source: Integrated System of Agricultural Products and Establishments - SIPEAGRO (2025)

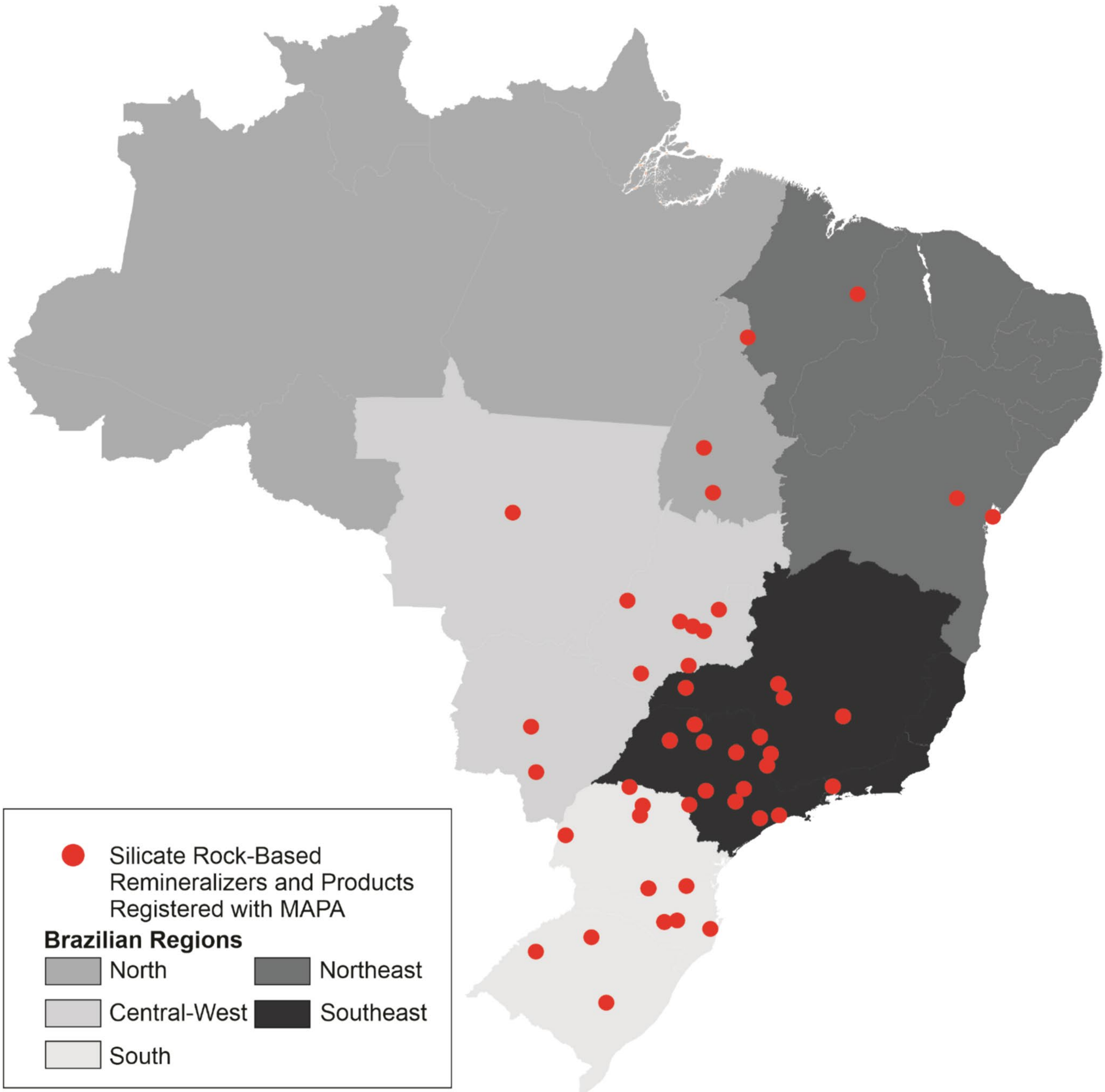


Fig. 6 Distribution of remineralizers and silicate rock-based products registered at Brazilian Ministry of Agriculture, Livestock, and Supply (MAPA) across the Brazilian regions
Adapted from the Geological Survey of Brazil - SGB (2025)

Table 3 Number of registered Soil Remineralizers (REMs) in each region of Brazil

Region	Number of registered REMs
Southeast	25
South	19
Central-West	19
Northeast	9
North	0
Total	**72**

Source: Integrated System of Agricultural Products and Establishments - SIPEAGRO (2025)

is established as a key strategy for agricultural sustainability, contributing to reducing dependence on conventional inputs and, consequently, mitigating the environmental and social impacts associated with the large-scale use of chemical fertilizers. In this regard, changes in legislation, the publication of regulations, and the establishment of protocols, such as those presented in Brazil by Silveira et al. (2019), represent significant milestones for the consolidation of REMs use.

4 Conclusions

This study shows that the Brazilian experience with soil remineralizers (REMs) provides a replicable model for other nations seeking to reduce their vulnerability in the fertilizer market and promote low-carbon agricultural practices. The dissemination of REMs in Brazil may be related to the enactment of Law No. 12,890/2013 and, in particular, Normative Instruction No. 5/2016, which consolidated their regulatory recognition as agricultural inputs. This institutional framework may have coincided with a marked increase in national scientific output, potentially contributing to Brazil's position among the leading countries in publications on this topic. Over the past two decades, research has shifted from conceptual studies to applied investigations in agricultural crops, particularly in areas such as agronomic efficiency, geochemical mechanisms, and CO_2 sequestration.

In conclusion, REMs stand out for their low cost, gradual nutrient release, suitability for tropical soils, and potential to reduce dependence on imported fertilizers, in addition to contributing to climate crisis mitigation. However, challenges remain, such as expanding research in underexplored regions and monitoring toxic elements. The trend points toward the expanded use and registration of REMs, reinforcing their relevance to food security and agricultural sustainability.

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Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent for Publication Not applicable.

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