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Magadiites in the Global Patent Landscape: a Recent Technological Prospecting Analysis (2020-2025) Based on the International Patent Classification

Magadiítas no Cenário Global de Patentes: uma Análise de Prospecção Tecnológica Recente (2020-2025) com Base na Classificação Internacional de Patentes

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Advances in the science, technology, and innovation of magadiite-based materials can be mapped through patent indicators. Technological prospecting enhances the interpretation of such indicators and offers insights into market trends, research directions, competitiveness, and policy planning aligned with scientific and technological progress. This article aims to analyze the global landscape of patents involving magadiites through a technological prospection approach based on the IPC. The methodology was structured in five steps: (i) collection of patents indexed in the Scopus database; (ii) manual screening to remove duplicate and irrelevant documents; (iii) application of inclusion and exclusion criteria; (iv) organization of the 164 resulting patents by year, country, institution, inventors, and IPC codes; and (v) data analysis. This approach enabled the identification of the United States, Japan, and Germany as the leading countries of magadiite-related patent filings. The Chemistry and Metallurgy category predominates in the global R&D landscape. This research highlights ongoing challenges related to structural modifications of magadiite, which are crucial for obtaining new materials with effective industrial applications. We conclude that technological prospecting based on IPC classifications provides valuable data for understanding global market demands, anticipating emerging technologies, identifying key areas and technological hotspots, and guiding new research in underexplored fields.

Keywords: Lamellar silicate; prospective meta-analysis; patent analysis; scientometrics; technological hotspots.

1. Introduction

Magadiite is a hydrated silicate mineral arranged in lamellae that can be found in nature or produced in the laboratory. Its origin is African,[1] and it is found in a highly alkaline lake with the formula $NaSi_7O_{13}(OH)_3\cdot 3H_2O$ and a basal spacing of 1.54 nm. However, it has also been discovered in volcanic rocks in the Pacific region of the United States of America.[2] Evidence shows that its synthetic form was first obtained in a laboratory in East Pittsburgh, Pennsylvania, by crystallizing an aqueous sodium silicate solution with NaOH at 100 °C for four weeks.[3] Considerable progress has been made in developing magadiites, and laboratory bench tests worldwide have provided evidence of experimental procedures suitable for industrial applications.

Since then, researchers have begun to optimize different synthesis methods, reproduce them under laboratory conditions similar to natural ones to obtain crystalline lamellar silicates, and are highly interested in their use as catalysts,[4–6] precursors in the construction of other inorganic materials,[7–9] molecular carriers,[10–12] supports,[4,13,14] adsorbent or absorbent materials,[15-17] and energy storage.[18-20] In addition, they realized that magadiite is easily synthesized without high economic or operational costs and that it presents some peculiar and modulable structural characteristics, such as the reversible hydration power of its lamellae; the replacement of its sodium cations by different organic or inorganic chemical species; the modification of the lattice *via* isomorphic replacement of silicon by metallic elements; and the ability to control different degrees of expansion of the basal spacing, which can configure potential uses in various industrial sectors, health, energy systems, and the environment.

In our recently published review study,[21] we chronologically outlined a robust body of references and traced the historical evolution of hypothetical structural models of magadiite, along with the development of various synthesis methods capable of producing magadiites with different formulations, including inorganic–inorganic and inorganic–organic hybrid materials. In addition to presenting diverse applications, we provided a comprehensive and critical analysis of future research directions, emphasizing magadiite's potential as a multifunctional material. Despite the advances achieved in the synthesis and application of magadiites, several challenges remain to be addressed - ranging from the production of pure, crystalline, active, and highly stable materials to in-depth structure-activity relationship studies, particularly in catalytic systems, sorption processes, carrier applications, and energy storage. Moreover, existing gaps - such as eco-friendly synthesis methods, structural modification and elucidation, integration with various organic or inorganic matrices, and especially applications in environmental technologies - underscore growing scientific and technological interest in magadiites. These gaps offer promising opportunities in emerging sectors that demand advanced and sustainable materials. Therefore, fostering collaboration and facilitating the transfer of patentable technologies between universities and industries is essential for advancing the Research and Development (R&D) landscape.

Collaboration between universities and industries has been studied and analyzed through patent indicators.[22-27] This fruitful relationship varies between areas or fields of science and types of technology. For example, Wu *et al.*[27] contributed to the R&D sector through a quantitative analysis of 1,883,593 patents in the pharmaceutical field, revealing how and to what extent science impacts technological development. Teng and Zhu,[25] with an analysis of citations of 6,901,428 patents, revealed a very close connection with science in the progress of Chinese technology, mainly in digital communication. Noruzi and Abdekhoda[23] analyzed 212 Iranian patents and concluded that Iran's main R&D application area is Chemistry and Metallurgy. Wei *et al.*[26] mapped 2273 patents on inorganic nanomaterials used in the diagnosis and treatment of cancer, concluding that scientific research developed in universities is a fundamental promoter of application in the R&D sector. Gazni[22] identified links with science and technology in 381,249 Chemistry and Metallurgy and Human necessities patents. Thus, it is clear that patentometric indicators have been useful in exploring science-technology interactions and that university-industry collaboration is essential for strengthening and advancing the R&D sector.

Within this scenario, patentometric indicators allow researchers and inventors to identify technological trends in different areas of science. The prospecting process is important for mapping where the most significant R&D investments occur, offering insights into market trends and industrial advances. Patent prospecting also allows the identification of the key actors - whether inventors, countries, universities, research centres, or leading industries.[23] Identifying the geographic distribution of patents makes it possible to define technological competitiveness, providing valuable data for planning more effective policies. Furthermore, patent analysis makes it possible to anticipate challenges and technological gaps by directing research into little-explored areas, allowing universities and industries to identify areas that can be further studied, promoting strengthening, collaboration, and adopting solutions or process improvements.[26]

To our knowledge, this is the first study in the scientific literature to undertake a technological prospecting analysis of patents related to magadiites. Accordingly, this work aims to examine the global patent landscape involving magadiites indexed in Scopus, and to identify and spatially represent the leading countries and research areas with the highest levels of technological and scientific activity. A temporal distribution of patents from 2020 to 2025 was conducted to identify trends, technological hotspots, and gaps in the magadiite field, based on the International Patent Classification (IPC). Analysing patent activity through the IPC provides an effective means of assessing the specialisation and scope of technological development across different sectors.[23] The IPC system is hierarchically structured into eight main sections, designated A to H (A – Human Necessities, B – Performing Operations and Transporting, C – Chemistry and Metallurgy, D – Textiles and Paper, E – Fixed Constructions, F – Mechanical Engineering, Lighting, Heating, Weapons, and Blasting, G – Physics, H – Electricity), and further subdivided into classes, subclasses, groups, and subgroups. This study provides a basis to inform policymakers, as well as to guide future research and technological development in universities, research institutions, and industry, particularly in strategic areas of R&D involving the development of new magadiite-based materials.

2. Experimental

The methodology adopted in this study was structured into five steps, as illustrated in the infographic presented in Figure 1. Each step was rigorously applied, enabling a comprehensive analysis of the global patent landscape related to magadiites. This methodological approach allowed for the mapping of technological trends; the spatial identification of countries, applicants, and leading inventors; and the examination of innovations across R&D areas, IPC classes, and subclasses. The results made it possible to identify both technological hotspots and existing gaps within the field of magadiites, highlighting emerging domains and industrial application sectors according to the IPC.

2.1. Data collection

This study, which aimed to identify patents related to magadiites, employed a patentometric approach based on the quantitative and qualitative analysis of documents indexed in the Scopus database - a renowned platform[28] that includes

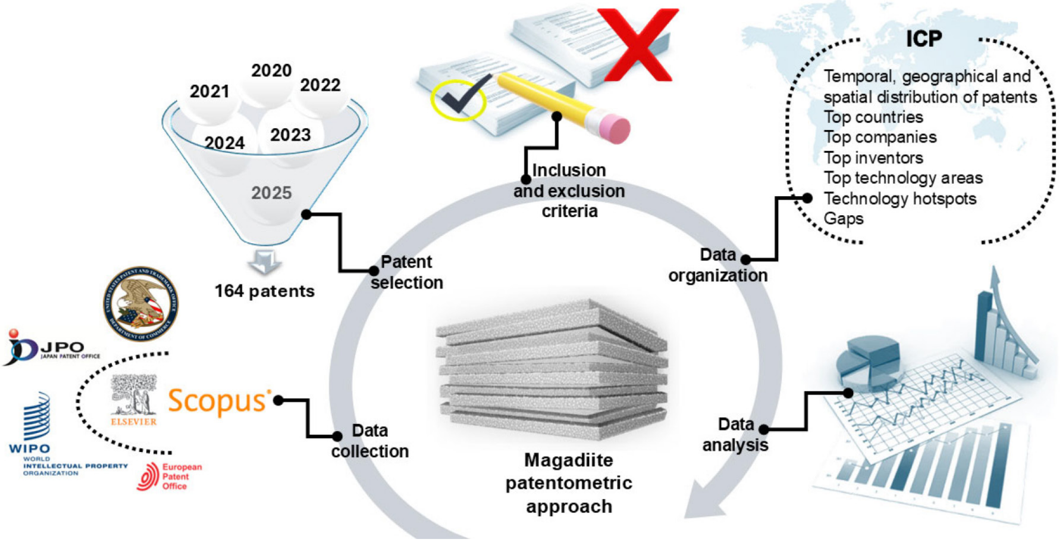

Figure 1. Infographic of the patentometric approach for technological prospecting of magadiite-related patents

both patent records and scientific publications. Scopus was selected for its comprehensiveness and its access to patent documents from several jurisdictions, including the United States Patent and Trademark Office (USPTO), the Japan Patent Office (JPO), the European Patent Office (EPO), and the World Intellectual Property Organization (WIPO). All data were collected on March 17, 2025.

2.2. Patent selection

The TITLE-ABS-KEY field was used in the Scopus search engine to retrieve patents focused on magadiite, ensuring comprehensive coverage. The search was restricted to the period from January 2020 to February 2025 in order to capture recent innovations and mitigate potential indexing delays in the Scopus database. The term "magadiite" (including linguistic and orthographic variations) was employed to identify relevant documents. A total of 471 patents were initially retrieved. To refine the dataset and eliminate duplicates or irrelevant records, a manual screening was conducted, considering the presence of the term "magadiite" in the title, abstract, or keywords, resulting in a final sample of 164 patents.

2.3. Inclusion and exclusion criteria

To ensure the relevance of the results, patents explicitly mentioning the use of magadiite in their claims or descriptions, as well as those published or granted from 2020 to February 2025, were included. Patents that were duplicated or did not contain the term "magadiite" in the title, abstract, or keywords were excluded.

2.4. Data organization and analysis

The data extracted from the Scopus database included the number of patents and their temporal distribution (2020-2025), as well as their geographic and spatial distribution at the global level. The analysis identified peaks of innovation and technological trends projected to continue through 2030; ranked countries according to patent output; identified the main actors responsible for filings - including companies, universities, and individual inventors; and classified patents by technological areas, IPC classes, and subclasses that most prominently reflect the use of magadiites.

The data used for the patentometric analysis were organized in spreadsheets to enable detailed quantitative and qualitative evaluations based on patent counts and IPC classifications. The initial phase of the analysis focused on temporal and geographic distribution patterns, highlighting the top three countries and institutions leading global R&D efforts related to magadiite, along with their principal inventors. The subsequent phase examined technological domains, with emphasis on the broad area of Chemistry and Metallurgy and its most relevant IPC classes and subclasses. The study concludes with insights into future research opportunities, informed by the identification of technological hotspots and gaps in the field of magadiite-based innovation.

3. Results and Discussion

3.1. Temporal distribution of patents, leading countries, institutions, and inventors

Analyzing the temporal evolution of magadiite-related patent filings serves as an important starting point for understanding the current landscape prior to examining the distribution of applications across different IPC classes and subclasses. As shown by the red dashed trend line in Figure 2, the number of global patent filings on magadiites between 2020 and 2025 reveals a gradual increase and a linear growth trend projected through 2030. This reflects the expansion of the R&D sector and, more significantly, the growing importance of this topic to the scientific community. Such a trend suggests the potential for advancing applied research models that strengthen ties between industry, research centers, and universities in response to societal needs. Furthermore, Figure 2 indicates that in 2023, 44 patents were filed, representing a 52% increase (23 patents) compared to 2020, which had 21 filings. This growth demonstrates a consistent rise in R&D activity over the past five years, despite a temporary decline observed in 2022, likely due to the lingering effects of the COVID-19 pandemic. With the post-pandemic recovery underway, the annual number of patent filings focused on the formulation and application of various magadiite-based materials is expected to continue increasing and may exceed the 52% growth threshold over the next decade.

Analyzing the volume of patent filings by leading countries and institutions engaged in R&D related to silica-based materials, such as magadiites, offers valuable insights into their innovation strategies, process development or improvement efforts, and technological competitiveness. Figure 3 illustrates the geographic, temporal, and spatial distributions of the primary countries and research entities—universities, institutions, and industries—that filed magadiite-related patents between 2020 and 2025. Among the 15 countries that submitted patent applications during this period, the United States led with 40 filings, followed by Japan (36) in East Asia and Germany (34) in Europe, establishing themselves as global leaders in patent activity. The geographical distribution indicates that Asia exhibits substantial interest and technological capacity in magadiite-related R&D, with particular emphasis on the Republic of Korea (18 patents), China (9), and the Republic of Singapore (4). Together with Japan, these countries account for 41% of the total patents filed worldwide. Notably, in 2023 (Figure 3b), Japan and Germany surpassed the United States in the number of filings, possibly reflecting global demand for technologies aimed at sustainability and renewable energy alternatives. In contrast, by 2024, the United States had regained its leading position.

The technological relevance of magadiites is closely linked to their multifunctionality. Over the past five years, several major American, Japanese, and German companies (Figure 3c) have shown growing interest in R&D focused on magadiite-based production and applications. For example, Chevron - one of the world's largest energy corporations operating in the petrochemical sector - filed 14 patents between 2020 and 2024 related to methods for catalyst preparation and application. Of these, 33% specifically address hydroisomerization catalysts, with Yihua Zhang, Senior Research Engineer at Chevron, listed as the lead inventor. Toppan, a global company founded in 1900 and headquartered in Japan, is recognized for its innovations in electronic materials (e.g., thin films and display technologies) and sustainable, recyclable packaging solutions. From 2020 to 2024, Toppan filed 16 patents related to magadiites; of these, 53% were submitted by Yoshiko Ishimaru as first inventor, primarily involving optical films and display devices. In Germany, the chemical sector demonstrated significant patent activity involving magadiite during the same period. Innovation efforts were concentrated in two major global corporations: Henkel and BASF. Their filings primarily targeted cleaning products and material development, with 22 and 4 patents, respectively. Notably, Christian Kropf is listed as the lead inventor in over 40% of Henkel's patents, particularly in the dishwashing detergent category, while Andrei-Nicolae Parvulescu contributed to 50% of BASF's filings related to zeolite preparation.

In addition to industrial, several universities engaged in R&D involving magadiite-type materials are also noteworthy. In the United States, Cornell University (a private institution), the University of California, and the

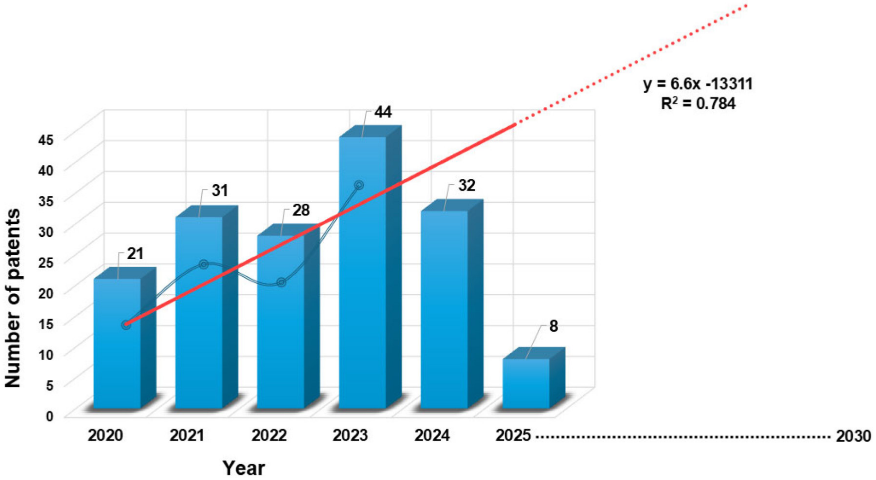

Figure 2. Global graph showing the temporal evolution of magadiite-related patent filings indexed in Scopus (from January 2020 to February 2025, a total of 164 patents), including the projected linear trend through 2030. Data retrieved on March 17, 2025

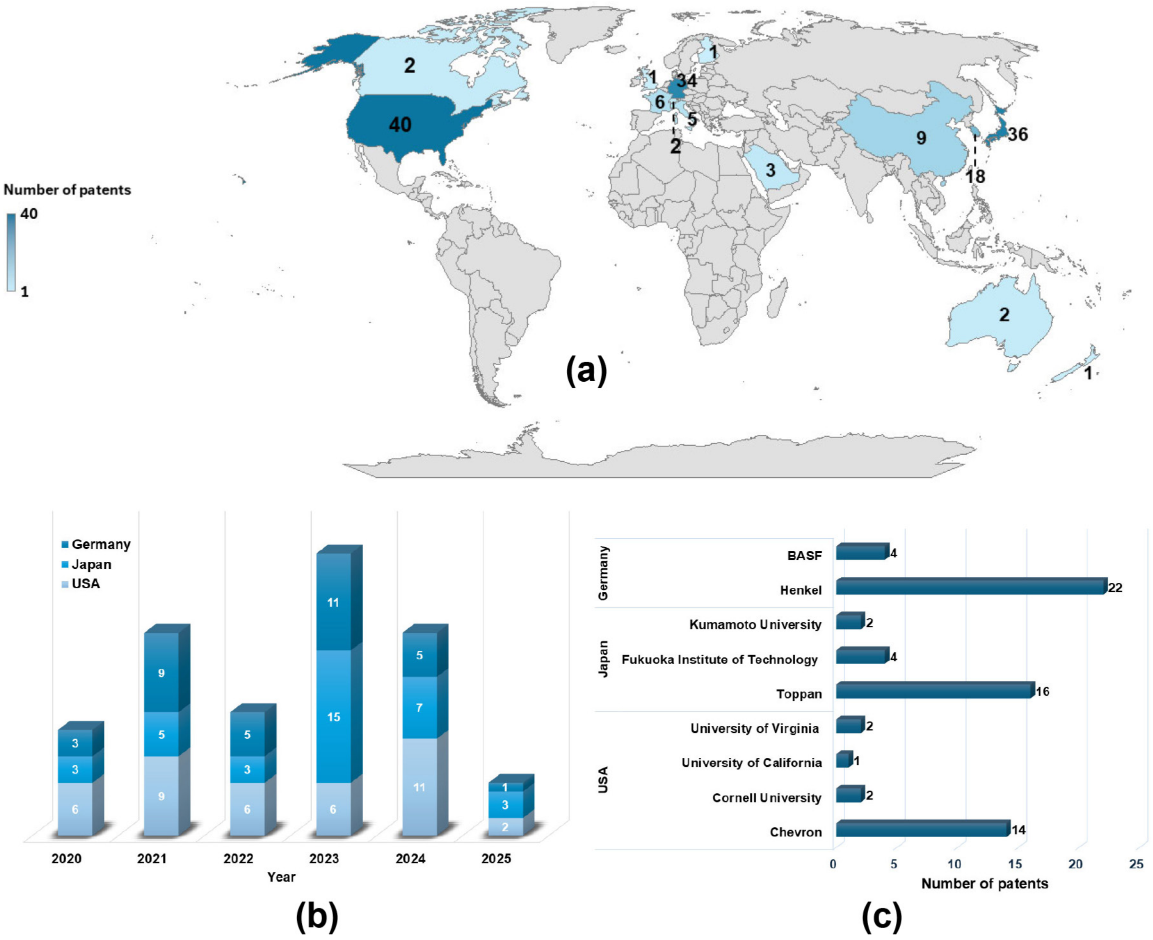

Figure 3. Number of patent filings related to magadiites indexed in Scopus (January 2020 to February 2025; total of 164 patents): (a) geographical; (b) temporal; and (c) spatial distributions of leading countries and institutions/industries in the global R&D landscape

University of Virginia (a public institution) collectively filed five patents (Figure 3c), accounting for 13% of all U.S. patents related to magadiites between 2020 and 2024. During the same period, the Fukuoka Institute of Technology and Kumamoto University filed six patents, representing 19% of Japan's total filings. This panorama underscores the strategic relevance of magadiite in global research and technological development. Although a few universities stand out, the overall number of patents remains relatively low, suggesting persistent gaps in innovation and technology development. These gaps point to the need for greater implementation, financial support, and institutional investment, as well as enhanced opportunities for alignment and technology transfer between academia and industry.

Additionally, Table 1 presents the top inventors from the aforementioned universities and details the corresponding applications according to IPC classifications. Among university-filed patents, technology D01D5/00 - related to methods or apparatuses specifically designed for forming filaments, lines, or similar structures - stands out as an emerging topic in the field of chemistry, particularly in connection with electrochemical technologies.[29] Other relevant technologies include B82Y40/00 (manufacturing or treatment of nanostructures), C01G23/053 (titanium compounds), C01G23/00 (niobium compounds), C01B33/32 (alkali metal silicates), and C01B33/38 (layered silicates), all of which are associated with the preparation of nanostructured catalysts. Patent applications in the field of nanotechnology grew at an average annual rate of 19% during the first and second decades of the 21st century - significantly higher than the 3.4% growth observed across all technological domains.[30] These figures highlight the growing impact of magadiites within the global R&D landscape of nanomaterials.

3.2. R&D areas, classes, and subclasses most prominent in the use of magadiites: identification of technological hotspots and gaps

Patent data organized according to the IPC highlight the value of combining quantitative patent analysis with an understanding of market demands and emerging technological trends. This integrated approach reveals not only areas of concentrated innovation but also future challenges and opportunities.[23] The radar charts in Figure 4 illustrate the technological and innovative potential of magadiites across various classification areas, emphasizing their versatility. Notably, 51% of all patents fall under IPC

Table 1. Top inventors from leading universities and industries in the global patent landscape related to magadiites and their applications, based on IPC classifications, as indexed in Scopus (January 2020 to February 2025)

	IPC	
Patent Number[a]	**Code**	**Application**
1st inventor (Applicant) - **ZHANG, Yihua (Chevron)**		
US2024076560A1 US11865527B2 US2024299918A1	B01J29/76	Catalysts comprising molecular sieves
WO2022153197A1	B01J21/04	Alumina catalysts
US2022219152A1	B01J35/02	Catalysts, in general, characterized by their shape or physical properties
1st inventor (Applicant) - **JOO, Yong L. (Cornell University)**		
US11728545B2 US2021399384A1	D01D5/00	Methods or apparatus specially adapted for forming filaments, threads, or the like
1st inventor (Applicant) - **MAIBACH, Howard I. (University of California)**		
US11344491B2	A61K8/04	Preparations for cosmetic or personal hygiene purposes (dispersions, emulsions)
1st inventor (Applicant) - **CLARENS, Andrés F. (University of Virginia)**		
US2022002203A1 US12209053B2	C04B22/06	Use of oxides or hydroxides as active ingredients for mortars, concrete, artificial stone, or similar
1st inventor (Applicant) - **ISHIMARU, Yoshiko (Toppan)**		
EP4283347A1 EP4283346A1 US2023375762A1 EP4279963A1	G02B5/22	Absorption filters as optical elements
US2023358932A1 US2023258930A1	B32B7/023	Layered products characterized by their optical properties
EP4283348A1	G02B1/116	Optical elements characterized by electrically conductive layers
US2023358931A1	G02B5/20	Filters as optical elements
1st inventor (Applicant) - **MIYAMOTO, Nobuyoshi (Fukuoka Institute of Technology)**		
US2024240027A1	B82Y40/00	Manufacturing or treatment of nanostructures
US2024101442A1	C01G23/053	Titanium compounds (wet process production)
EP4335822A1	C01G23/00	Niobium compounds
EP4209459A1		Titanium compounds
1st inventor (Applicant) - **IDA, Shintaro (Kumamoto University)**		
US2024132365A1	C01B33/32	Preparation of alkali metal silicates
EP4299521A1	C01B33/38	Preparation of base exchange layered silicates
1st inventor (Applicant) - **KROPF, Christian (Henkel)**		
US2023272307A1 US11702616B2 US2021269746A1 US2021087496A1	C11D11/00	Unique methods for the preparation of compositions containing detergent mixtures
WO2022100949A1 US2024327756A1	C11D3/16	Organic compounds of detergent compositions based essentially on surface-active compounds
US2024263103A1	C11D17/04	Detergent materials characterized by their shape or physical properties combined with or containing other objects
WO2023117380A1	C07D273/08	Heterocyclic compounds have two nitrogen atoms and more than one oxygen atom
WO2023099154A1	C07C50/18	Preparation of anthraquinones
US2024301329A1	C11D3/20	Oxygen-containing compounds of detergent compositions
1st inventor (Applicant) - **PARVULESCU, Andrei-Nicolae (BASF)**		
US11554964B2 US2021198114A1	C01B39/04	Compounds having molecular sieve and base-exchange properties using at least one directing agent

[a] The patent number can be used to search for other data at https://worldwide.espacenet.com/patent/

section C (Chemistry and Metallurgy), indicating that magadiites are predominantly applied in chemical processes. These include their use in material compositions,[31-33] cleaning agents,[34-36] and the preparation of compounds containing metals and nonmetallic elements,[37-39] with German companies like Henkel and BASF and several Japanese universities as key contributors. Furthermore, 27% of the patents belong to section B (Performing Operations and Transporting), reflecting applications in industrial and manufacturing processes, particularly as catalysts and adsorbents,[40-42] with Chevron standing out in the United States. Section G accounts for 9% of the patents, related to the measurement and control of physical systems, especially optical films—an area led by Toppan in Japan.[43-45] An additional 9% are categorized under section A (Human Necessities), pointing to potential uses in cosmetics, personal care products, and agricultural applications.[46-48] Although less prominent, section H (Electricity) accounts for 3% of the patents, suggesting emerging interest in electrical applications such as electrode fabrication, secondary galvanic cells, and materials with conductive, insulating, or dielectric properties.[49-51] Overall, this panorama underscores the significant multisectoral innovation capacity of magadiites. Their broad reach across diverse R&D areas and strong industrial and academic appeal reinforces their potential to contribute meaningfully to technological, scientific, economic, and environmental advancements.

The technological potential of magadiites is particularly evident within the two major IPC sections: Chemistry and Metallurgy (83 patents) and Performing Operations and Transporting (44 patents), as demonstrated by the prevalence of filings in classes C08, C11, C01, C09, B01, and B32 (Figure 4b). Class C08 (37 patents) underscores the extensive use of magadiites in the chemistry of organic macromolecular compounds, particularly in the preparation of polymers through reactions not involving unsaturated C–C bonds.[52-54] In class C11 (17 patents), magadiites are linked to the chemistry of oils, fats, fatty substances, and animal or vegetable waxes, while in class C01 (14 patents), they are relevant to Inorganic Chemistry, especially for processes involving the synthesis and modification of layered polysilicates.[37,39,55] Class C09 (11 patents) reflects applications related to the formulation and use of adhesive materials.[32,56,57] Within industrial process technologies, class B01 (26 patents) addresses the use of magadiites in physical and chemical separation and mixing methods, highlighting their role in catalytic systems and composite materials.[58-63] Class B32 (8 patents) focuses on the development of layered products, particularly in advanced film technologies.[43,64,65] Collectively, these data reinforce the high technological value of magadiites, demonstrating their wide applicability across various chemical and industrial domains.

Figure 5 presents the distribution of patent classes C08, C11, C01, and C09 across their respective subclasses related to magadiites within the field of Chemistry and Metallurgy. This detailed breakdown enables the identification of functional specificities, technological hotspots, and development gaps in applications of magadiites across diverse sectors.

In class C08, which encompasses organic macromolecular chemistry (Figure 5a), the largest concentration of patents is found in subclasses C08G, C08L, and C08K, signaling a hotspot in the formulation of compositions involving macromolecular and non-macromolecular compounds. Subclass C08G (24%) includes patents related to polymeric products (e.g., C08G18/20, C08G73/10, C08G73/02, C08G63/60, and C08G18/16), exploiting the capacity of magadiites to enhance material strength and durability. Subclass C08L (19%) highlights their integration into polymer compositions (C08L7/00, C08L19/00, C08L23/22, and C08L61/06), particularly for applications leveraging their lamellar expansion properties. Similarly, C08K (19%) focuses on magadiites as ingredients in composite formulations (C08K3/30, C08K3/34, C08K3/22, and C08K9/04), where their reinforcing capacity is utilized.

Other subclasses, including C08J (14%), which addresses processing methods for polymer mixtures (C08J3/215), and C08F (11%), which involves the synthesis of macromolecular compounds *via* unsaturated C–C bonds (C08F236/12, C08F10/02, and C08F210/12), show moderate patent activity. Meanwhile, C08C (8%),

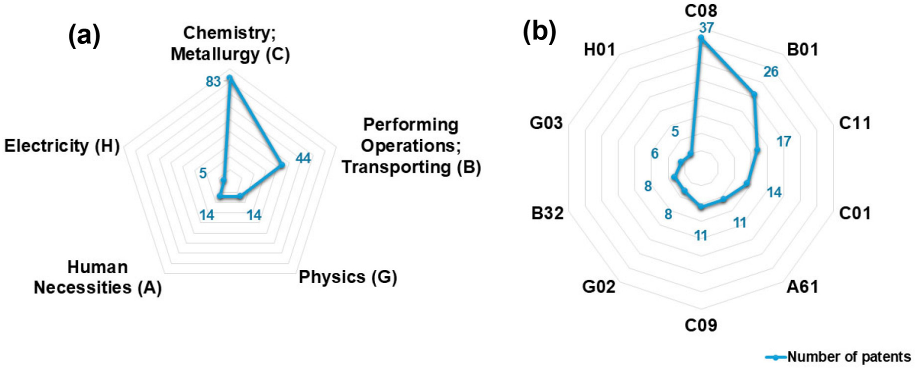

Figure 4. Radar charts showing the number of magadiite-related patent filings by scientific and technological development areas, based on IPC classifications and indexed in Scopus (January 2020 to February 2025): (a) main R&D application areas; and (b) the ten IPC classes with the highest number of patents

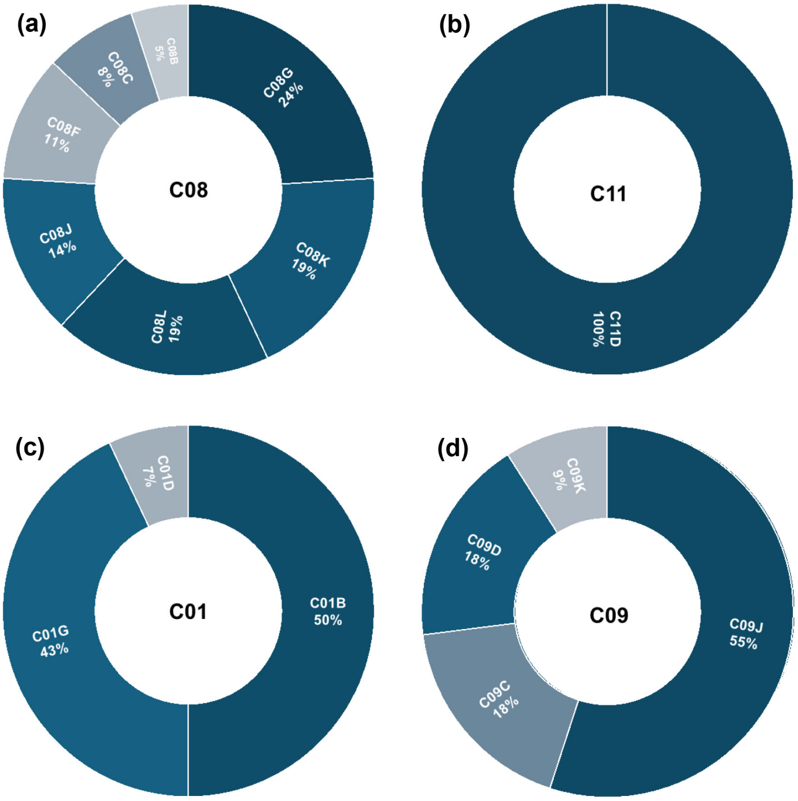

Figure 5. Subclasses of patents related to magadiites in the Chemistry and Metallurgy section, indexed in Scopus (January 2020 to February 2025): (a) subclasses within the chemistry of organic macromolecular compounds; (b) subclasses within the chemistry of oils, fats, fatty substances, or animal and vegetable waxes; (c) subclasses within Inorganic Chemistry; and (d) subclasses within the chemistry of dyes, inks, polishes, natural resins, and adhesives. The quantitative analysis, expressed as percentages, refers to the total number of patents within each main IPC class

related to chemical modifications of rubber (C08C19/12), and C08B (5%), dealing with the preparation of natural polymers (C08B37/14 and C08B15/00), exhibit relatively lower numbers of patents. These figures suggest potential opportunities for future research in novel hybrid materials and applications involving biopolymers.

In the chemical class related to oils, fats, fatty substances, or animal and vegetable waxes (Figure 5b), subclass C11D is predominant, accounting for 100% of the patents concerning detergent compositions and glycerol recovery. The use of magadiites in this context focuses on the modification of fatty acids and their derivatives, particularly in preparation methods and detergent formulations primarily based on surfactant compounds (C11D11/00, C11D17/04, C11D3/16, C11D1/66, and C11D3/39). In these applications, the adsorption capacity, hydrophobicity, and ion-exchange properties of magadiites enhance the effectiveness of cleaning processes and the treatment of fatty acid derivatives.

Within the IPC class C01 – Inorganic Chemistry (Figure 5c), the C01B subclass accounts for 50% of the patents and stands out as a technological hotspot for the preparation of metallic and nonmetallic compounds, in which magadiites are primarily employed as ion exchangers (C01B33/38 and C01B39/04). The significant share of patents in the C01G subclass (43%), which relates to metallic compounds, highlights the use of magadiites in catalytic processes—particularly in the synthesis of titanium, niobium, and zirconium compounds (C01G23/053, C01G33/00, and C01G25/00). These applications take advantage of the ion-exchange capacity of magadiites, enabling enhanced control over basal spacing, morphology, acidity, and porosity, and resulting in materials with tunable and desirable properties.[21] Conversely, the C01D subclass (7%), focused on alkali metal compounds (C01D13/00), shows limited patent activity, pointing to a technological gap and suggesting an area with strong potential for further development, especially in specialized catalytic or separation processes.

In class C09 (Figure 5d), which encompasses the chemistry of dyes, inks, polishes, natural resins, and adhesives, the focus on subclass C09J (55%) reveals a clear technological hotspot in the preparation of organic and inorganic adhesives (C09J11/00, C09J101/02, C09J189/00, and C09J123/22). These patents reinforce the role of magadiites as agents capable of enhancing adhesion, mechanical strength, and durability. In contrast, the smaller proportions of patents in subclasses C09C and C09D (18% each), as well as C09K (9%), highlight gaps in the application of magadiites in formulations for pigments, coatings, and specialized compositions (C09K8/68, C09C1/46, C09D123/06, and C09D131/04). These technological areas could benefit significantly from the surface modification properties offered by magadiites.

This overview underscores the versatility and technological potential of magadiites in a wide range of applications, particularly in advanced chemical processes and the development of high value-added materials. While magadiites have been extensively explored in sectors such as polymers, adhesives, and catalysis, opportunities for innovation remain in areas involving biopolymers, specific metallic compounds, and formulations for paints and coatings. These technological gaps indicate promising directions for R&D, especially in refining preparation methods, engineering novel compositions and material systems, and expanding applications into emerging sectors such as electricity, human needs, composite materials, and green technologies.

3.3. Methodological challenges and territorial invisibilities in the global understanding of innovation involving magadiites

Although magadiite presents diverse technological potential, important gaps remain that represent both challenges and opportunities for the advancement or development of future research. Through the analysis of patents, this work revealed that one of the main challenges is related to mastering the methods of synthesis and modification of magadiites, especially in the preparation of hybrid materials to ensure their application in the sectors of biopolymers, catalysis, adsorption, and compositions in pigments and coatings. These applications represent research opportunities to develop sustainable solutions, more efficient and eco-friendly heterogeneous catalysts, and innovative materials exploiting modified magadiite's mechanical, optical, thermal, and hydrothermal properties. The development of controlled modification processes that maximize the functionality of magadiites is a field that leads to opportunities that need to be better explored, which can lead to new materials and promote innovation. Furthermore, when new magadiites are being prepared, one point to consider is that production is economically viable. Thus, new synthesis methodologies should be designed to support laboratory-scale experiments while enabling scalable and cost-effective processes suitable for industrial applications.

Based on the proposed methodology, we emphasize that the patentometric approach specified in this study was grounded in both qualitative and quantitative data extracted from patents indexed in the Scopus database. This analysis enabled the identification of trends, temporal developments, and geographic distributions of technological innovation related to magadiites on a global scale. However, the analysis relied exclusively on documents indexed in *Scopus*, which, although ensuring the quality and standardization of records,[28] excludes filings submitted to other patent offices not integrated into the database, such as Brazil's INPI. We consider this the primary limitation of our analysis.

Another limitation concerns the partial nature of the patent records, as some discrepancies may result from delays in the indexing and publication process within the Scopus database. This is due to the fact that data collection was conducted in March 2025, and some of the filings may still be under private ownership. Furthermore, the data for 2025 reflect only registrations indexed up to February, implying that the information for that year is still undergoing consolidation and may be subject to considerable changes in future analyses. Therefore, we recommend caution when interpreting the emerging trends identified in the final year analysed (Figure 2), as these should be regarded as indicative rather than definitive.

Also notable in the distribution of patents, as shown in the global map in Figure 3(a), is the absence of developing and underdeveloped countries from Latin America and the African continent - particularly Brazil - which suggests not only territorial inequality, institutional barriers, and a lack of systematic research support or limited integration between universities and the private sector, but also a global hierarchy of scientific and technological knowledge.[25,66] The absence of patents originating from Brazil and the rest of Latin America, as well as from the African continent, can be interpreted as a reflection of the international division of scientific labour, in which knowledge production serves as an expression of power that remains subordinated to unidirectional flows of intellectual, legal, and financial capital.[67] In assessing the global and national technological impact of Chinese scientific output - based on patent citations in scientific articles and the analysis of the science–technology relationship - Teng and Zhu[25] stated that analyses involving developing countries are rare due to the lack of connection between academia and industry, as well as the low priority given to public and private investment in science to support economic development. Thus, we understand that the obstacles observed and discussed are not merely operational but involve geopolitical barriers that hinder a comprehensive view of innovation.

Within this scenario and considering the recent technological advances highlighted in this study, we emphasize the undeniable importance of further strengthening the ties between universities, industry, and both the public and private sectors through scientific research. This entails democratizing science, foster systematic collaborations and investments to implement actions that reduce territorial invisibility, address the demands of the science–technology interface, and promote sustainable development - environmental, social, and economic. Furthermore, a promising way for future studies, with the goal of increasing the precision of patentometric analysis and enriching the understanding of the disruptive potential of magadiite-based technologies worldwide, will require the adoption of complementary approaches.[68-72]

4. Conclusion

This article analyses the scientific and technological potential of magadiite on the global stage from 2020 to February 2025. The temporal distribution, key countries, leading institutions, inventors, technological areas, and IPC classes and subclasses have been systematically examined, allowing the identification of technological hotspots and gaps to inform future research directions. Compared to 2020, the number of patents filed in 2023 increased by 52%, and this percentage is likely to be surpassed over the next five years. This growth is directly linked to the potential for structural modifications of magadiite - particularly adjustments in basal spacing - to obtain materials with unique and attractive properties for industry and emerging applications. Among the 15 countries with patents indexed in Scopus between 2020 and 2025, the United States (40 patents), Japan (36), and Germany (34) led the ranking. Accordingly, the volume of patents related to magadiite applications across different R&D sectors reflects the technological competitiveness and scientific interest of each country and its respective industries, such as Chevron (14 patents) in the United States, Toppan (16) in Japan, and Henkel (22) and BASF (4) in Germany, focusing on the development of hydroisomerization catalysts, optical films and display devices, cleaning products, and advanced materials. In contrast, relatively few universities appear among the leading applicants, which may suggest limited academic involvement or weak university–industry collaboration.

Among the eight R&D areas defined by the IPC, five included patent applications related to magadiite. The area of Chemistry and Metallurgy (coded as C) stands out, accounting for 51% of all patents filed globally over the past five years. In contrast, the area of Electricity (coded as H), with only 3% of the total patents, is the least represented, suggesting a potential field for further exploration. Within the Chemistry and Metallurgy category, the IPC classes with the most significant contributions include: organic macromolecular compounds (C08, 37 patents); chemistry of oils, fats, and waxes (C11, 17 patents); Inorganic Chemistry (C01, 14 patents); and the chemistry of dyes, paints, polishes, resins, and adhesives (C09, 11 patents). Progress in these classes has not only advanced the understanding of magadiite chemistry but has also enabled the development of multifunctional materials with moldable properties. Ultimately, patent prospecting plays a crucial role in ensuring that researchers, inventors, and industries remain at the forefront of technological innovation, seizing opportunities to expand the application of magadiite in industrial and sustainable processes and fostering a continuous cycle of science, technology, and innovation.

Declarations

The authors declare that they have no competing financial interests.

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