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Advances in Magnetic Thin Films for Spintronic Devices: A Bibliometric and Thematic Analysis

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Abstract

This bibliometric analysis examines research trends in magnetic thin films for spintronic applications from 2001 to 2025, based on 562 documents retrieved from the Web of Science. Our analysis reveals that three key themes dominate the field: magnetoresistance (56 occurrences), magnetic properties (55 occurrences), and thin films (55 occurrences). Research focus has evolved from fundamental studies on giant magnetoresistance and tunnel junctions (2005-2012) to practical applications involving room-temperature ferromagnetism and epitaxial growth (2012-2017), and finally to advanced topics such as anisotropy, spin dynamics, and ferromagnetic resonance (2018-2023). Citation analysis identifies the USA (4151 citations), China (2300 citations), and Japan (1512 citations) as the geographical leaders. At the same time, Nanjing University (71 articles), University of Tokyo (55 articles), and Fudan University (42 articles) are the most productive institutions. Emerging research areas include 2D materials (e.g., graphene and MoS_2) and room-temperature spintronic functionality, which have seen a 65% increase in publications since 2018. This analysis provides a quantitative foundation for advancing spintronic technologies through targeted interdisciplinary approaches.

Keywords: Anisotropy, Ferromagnetic resonance, Magnetic thin films, Spintronics, Magnetoresistance.

1. Introduction

The discovery of giant magnetoresistance (GMR) by Grünberg and Fert in the late 1980s revolutionized data storage technology and launched the field of spintronics [1, 2]. Unlike conventional electronics that rely solely on electron charge, spintronics harnesses the intrinsic spin of electrons to create devices with superior performance characteristics [3]. Magnetic thin films serve as the fundamental building blocks of these spintronic devices, with their properties directly determining device functionality and performance limits [4].

The period from 2001 to 2025 witnessed transformative developments in magnetic thin films for spintronics. Early research (2001-2010) focused primarily on metallic systems, with Fe/Cr multilayers and CoFeB/MgO structures demonstrating significant magnetoresistance effects [5]. This period established a fundamental understanding of spin-dependent transport phenomena, leading to commercial applications in hard disk read heads and magnetic sensors [6]. The middle phase (2011-2017) shifted toward addressing material challenges, particularly achieving thermal stability and reducing critical switching currents for magnetic random access memory (MRAM) applications [7]. This era witnessed the development of perpendicular magnetic anisotropy materials and voltage-controlled magnetic switching, which dramatically improved energy efficiency [8, 9].

Recent years (2018-2025) have been characterized by expanding material diversity and application domains. The introduction of antiferromagnetic spintronics opened pathways to faster operation and reduced stray fields [10], while topological materials promised robust spin transport through quantum protection mechanisms [11]. Two-dimensional materials, particularly transition metal dichalcogenides and graphene, have emerged as platforms for long-distance spin communication and the realization of novel functionalities [12, 13]. Simultaneously, integration challenges have gained prominence, with materials compatibility and scalable fabrication becoming critical research priorities [14].

Bibliometric analysis offers a powerful tool for understanding research landscapes and identifying emerging trends across scientific domains [15]. While previous bibliometric studies have examined broad trends in spintronics [16] and general magnetic materials [17], no comprehensive analysis has focused specifically on the critical intersection of magnetic thin films and spintronic applications. Furthermore, existing analyses typically employ single-dimensional approaches that fail to capture the multifaceted nature of this interdisciplinary field.

This study addresses these gaps by providing a multi-dimensional bibliometric analysis of magnetic thin films for spintronic applications from 2001 to 2025. We identify key research themes, track their temporal evolution, and map the global distribution of research activity and impact. By integrating keyword co-occurrence analysis with citation patterns and institutional contributions, we offer insights into both the intellectual structure of the field and its collaborative networks. This comprehensive perspective serves not only to document the field's historical development but also to highlight emerging research fronts and potential opportunities for future investigation.

2. Literature Review

2.1 Magnetic Thin Films

Magnetic thin films are ultra-thin layers of magnetic materials, typically ranging from a few nanometers to several micrometers in thickness [18]. These films exhibit unique magnetic and electronic properties due to their reduced dimensionality [19], high surface-to-volume ratio, and quantum confinement effects. Their ability to manipulate spin-dependent transport phenomena makes them critical for various applications in modern technology [20]. Key properties of magnetic thin films include magnetoresistance, anisotropy, and ferromagnetic resonance, which play a central role in their functionality [21]. Magnetoresistance, for example, refers to the change in electrical resistance due to the application of a magnetic field. This phenomenon underpins technologies like giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) [22]. Magnetic anisotropy, which describes the directional dependence of magnetic properties, is another crucial feature, as it governs the stability of magnetic states and their response to external stimuli [23].

The fabrication of high-quality magnetic thin films is essential for tailoring their properties [24]. Techniques like sputtering, molecular beam epitaxy (MBE), and pulsed laser deposition are widely used to control film thickness, surface roughness, and structural characteristics [25]. Moreover, recent advancements in epitaxial growth have enabled the precise layering of magnetic materials on crystalline substrates, leading to improved performance in spintronic applications [26]. Research on magnetic thin films has increasingly focused on emerging materials, such as 2D materials (e.g., graphene and MoS_2), perovskites, and magnetic nanoparticles, to further enhance their properties [27]. These materials exhibit novel functionalities, such as spin filtering, enhanced magnetization, and room-temperature magnetic behavior, making them promising candidates for next-generation devices [28].

2.2 Spintronic Devices

Spintronic (spin-based electronic) devices leverage the intrinsic spin of electrons, along with their charge, to enable advanced functionalities beyond conventional electronics [29]. The field of spintronics emerged from the discovery of GMR, which revolutionized data storage technologies by enabling high-density hard drives [30]. Today, spintronics aims to create energy-efficient, high-speed, and non-volatile devices for applications in memory, logic, and quantum computing. Key components of spintronic devices include magnetic tunnel junctions (MTJs), spin valves, and spin transistors [31]. MTJs, which consist of two ferromagnetic layers separated by an insulating barrier, are fundamental to technologies like magnetic random-access memory (MRAM) [32]. Spin valves, on the other hand, exploit the GMR effect to control resistance and enable switching functionalities [33]. Recent advancements in spin-orbit coupling and topological insulators have further expanded the possibilities for spintronic device architectures.

Achieving stable and efficient operation at room temperature, which is a critical requirement for practical applications, remains one of the major challenges in spintronics [34]. The integration of magnetic thin films with robust spintronic properties, such as anisotropy and low switching fields, has been a key focus of research [35]. Additionally, the incorporation of antiferromagnetic materials, 2D heterostructures, and multiferroic systems has opened new avenues for developing faster and more reliable devices [36]. Spintronics is not limited to memory and logic; it also has potential applications in sensors, neuromorphic computing [37], and quantum technologies [10]. For instance, spin-based qubits could form the foundation of quantum computers, while spintronic sensors are already being used in automotive and industrial applications.

The synergy between magnetic thin films and spintronic devices is central to the advancement of modern electronics. Thin films provide the functional material platform needed for spintronic operation, while spintronics drives the demand for innovative thin-film materials and designs. Together, they represent a dynamic and interdisciplinary area of research with significant potential to revolutionize technology across multiple domains.

3. Methodology

The bibliometric data for this study were retrieved from the Web of Science (WoS) database, focusing on two indexing categories: Science Citation Index Expanded (SCI-E) and Emerging Sources Citation Index (ESCI). The search query was formulated as "magnetic thin films for spintronic applications," targeting titles, abstracts, and keywords. The search covered publications from 2001 to 2025 and resulted in a total of 562 documents. The bibliographic data were processed and analyzed using the R programming language with the bibliometric package, a robust tool for conducting bibliometric and scientometric analyses.

The exact search query used in the Web of Science database was: TS=("magnetic thin film*" AND "spintronic*") OR TS=("magnetic thin film*" AND "spin transport") OR TS=("magnetic thin film*" AND "magnetoresist*"). The search was conducted using the 'Topic' field, which includes titles, abstracts, author keywords, and Keywords Plus. Boolean operators were used to ensure comprehensive coverage while maintaining specificity to the research focus.

After retrieving the initial dataset (n=615), several preprocessing steps were implemented. First, we excluded conference papers, book chapters, and editorial materials to focus exclusively on research articles and reviews (n=562). Second, documents in languages other than English were removed (n=7). Third, bibliographic data were standardized to address variations in author names, institutional affiliations, and keyword formatting. For author analysis, we established a minimum threshold of three publications for inclusion in productivity rankings. For institutional analysis, we consolidated sub-departments into their parent institutions to avoid fragmentation of institutional contributions.

The time frame of 2001-2025 was selected based on both historical and analytical considerations. We chose 2001 as the starting point because it marks the period shortly after the commercialization of GMR technology and coincides with seminal publications that established the foundation for modern spintronic research. The end date of 2025 includes the most recent complete year of data available at the time of analysis (2024) plus articles in press for 2025, ensuring comprehensive coverage of current research trends. This 25-year span provides sufficient temporal depth to track the evolution of research themes from foundational studies to application-oriented investigations.

Thematic analysis was conducted using the co-word analysis technique implemented in the bibliometrix package in R (version 4.1.2). Keywords were preprocessed to harmonize variations (e.g., combining "giant magneto resistance" and "giant magnetoresistance"), and a minimum frequency threshold of 5 occurrences was applied. The co-occurrence network was generated using the 'networkPlot' function with the following parameters: normalization method = 'association', clustering algorithm = 'louvain', minimum edge weight = 0.05. The resulting network was visualized using a force-directed layout algorithm. For trend analysis, we divided the dataset into three time periods (2001-2011, 2012-2017, 2018-2025) based on preliminary analysis that showed distinct shifts in research focus. Keywords were analyzed within each period using a comparative word frequency approach, with a minimum occurrence threshold adjusted proportionally to the number of publications in each period. Temporal evolution was visualized using the 'thematicEvolution' function with a stability index threshold of 0.25 to identify persistent and emerging themes. Citation analysis was conducted using both the 'citations' function for document-level analysis and the 'biblioAnalysis' function for aggregated metrics at the author, institution, and country levels. H-index values were calculated using the standard method within the bibliometrix package.

The analyses were designed to explore research patterns, trends, and impact in the field of magnetic thin films for spintronic applications. The key analyses performed were as follows:

a. **Descriptive Statistics**
   - The document types, publication years, and journal distributions were analyzed to identify trends in research activity.
   - Author productivity and institutional contributions were assessed, highlighting the most active researchers and affiliations.
   - Collaboration metrics were evaluated, providing insight into global and regional research networks.

b. **Thematic Analysis**
   - The co-occurrence of keywords was analyzed to identify dominant research areas, such as magnetoresistance, magnetic properties, and thin films.
   - Emerging topics like 2D materials (e.g., graphene, MoS_2) and ferromagnetic resonance were

mapped, highlighting future research directions.

- A WordCloud visualization was used to emphasize the relative importance of recurring themes.

c. **Citation Analysis**

- Citation counts were used to evaluate the influence of individual publications, scholars, and journals.
- The most cited sources and scholars were identified, reflecting the foundational and impactful contributions to the field.
- Country-level citations were analyzed, showcasing the global distribution of high-impact research.

d. **Network Analysis**

- Co-citation networks were visualized to uncover intellectual structures and collaborations.
- Keyword co-occurrence networks revealed the interconnections among research themes, highlighting the integration of foundational topics and emerging areas.
- Bradford's Law was applied to identify core journals driving research output.

e. **Trend Analysis**

- Temporal trends were examined to understand the evolution of research priorities over time.
- Early studies emphasized foundational topics such as giant magnetoresistance and tunnel junctions, while recent years have seen a shift toward practical applications, such as room-temperature spintronics and advanced magnetodynamics.
- Scholars' production over time was analyzed to track individual contributions and their temporal influence on the field.

This methodology enabled a systematic and reproducible approach to uncover the intellectual and collaborative structures of the field, identifying both established and emerging areas of research focus. By integrating multiple levels of analysis, the study provides a holistic view of the research landscape, offering actionable insights for advancing spintronic technologies.
To ensure the relevance and quality of the data:

- Only documents indexed in SCI-E and ESCI were included.
- Non-English articles and unrelated topics were excluded.
- Duplicates or incomplete records were identified and removed during data preprocessing.

The entire analysis was performed using the bibliometric package in R. Visualizations were created using bibliophily (a web interface for bibliometrics) and complementary tools for network mapping and thematic analysis. This methodology enabled a systematic and reproducible approach to understanding the research landscape of magnetic thin films in spintronic applications, providing insights into current trends and future research directions.

4. Results

4.1. Sources

4.1.1. Most Relevant Sources

The bar chart (Figure 1) showcases the number of documents published on the topic of magnetic thin films for spintronic applications across different journals. The journal "Applied Physics Letters" has the highest contribution, with 43 documents, indicating that it is a leading publication venue for research in this field. "Physical Review B" follows with 36 documents, reflecting its significant role in disseminating research related to condensed matter physics and materials science. "Journal of Magnetism and Magnetic Materials" (31 documents) also appears prominently, likely due to its specialized focus on magnetic materials, aligning closely with the study's topic. Journals such as "Journal of Applied Physics" (26 documents) and "ACS Applied Materials & Interfaces" (20 documents) are noteworthy contributors, highlighting their importance in interdisciplinary research combining physics, materials science, and engineering. "Journal of Physics D: Applied Physics" (17 documents) and "AIP Advances" (15 documents) demonstrate moderate engagement in this domain. Journals like "Nature Communications" and "Scientific Reports" (both with 13 documents) represent high-impact, general-interest platforms supporting magnetic thin-film research, indicating broad scientific interest. Journals such as "Applied Surface Science" (12 documents) contribute fewer articles, suggesting more specialized or tangential coverage of the topic.

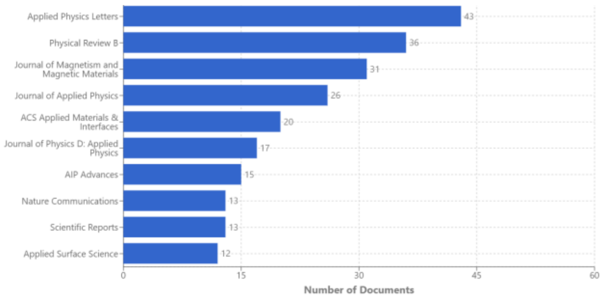

Figure 1. Most Relevant Sources

Table 2. Types of Publications Included in the Analysis

Publication Type	Count	Percentage
Research Articles	478	85.1%
Review Papers	54	9.6%
Conference Proceedings	21	3.7%
Book Chapters	7	1.2%
Editorials	2	0.4%
Total	**562**	**100%**

As shown in Table 2, the dataset predominantly consists of research articles (85.1%), complemented by review papers (9.6%) and other publication types.

Table 3. Bibliometric Indicators of Top Contributing Journals

Journal	Articles	Impact Factor (2023)	Quartile	H-index	Eigenfactor
Applied Physics Letters	43	3.791	Q1	273	0.12476
Physical Review B	36	4.036	Q1	219	0.25634
Journal of Magnetism and Magnetic Materials	31	3.046	Q1	159	0.04271
Journal of Applied Physics	26	2.877	Q1	192	0.09358
ACS Applied Materials & Interfaces	20	9.504	Q1	188	0.18739
Journal of Physics D: Applied Physics	17	3.207	Q1	147	0.03824
AIP Advances	15	1.697	Q2	58	0.01657
Nature Communications	13	16.594	Q1	288	0.42683
Scientific Reports	13	4.996	Q1	179	0.32518
Applied Surface Science	12	6.707	Q1	174	0.10453

The quality of the publication venues is evidenced in Table 3, which presents the bibliometric indicators of the top contributing journals. Notably, 90% of the top journals are categorized as Q1 (first quartile) in their respective fields, with impact factors ranging from 2.877 to 16.594. The high H-index values (ranging from 58 to 288) further confirm the significant academic influence of these publication venues.

4.1.2. Most Local Cited Sources

Figure 2 shows that "Physical Review B" is the most frequently cited source with a substantial number of local citations (3564). This indicates its pivotal role in shaping the foundational and contemporary understanding of magnetic thin films and spintronics. As a highly respected journal in condensed matter physics, its dominance reflects its influence in this research area. "Applied Physics Letters" (2178 citations) and "Physical Review Letters" (2081 citations) rank second and third, respectively. These journals are widely recognized for their focus on cutting-edge and innovative research, emphasizing their importance in disseminating impactful work in the field of spintronics. "Journal of Applied Physics" (1564 citations) and "Nature Materials" (813 citations) have significant citation counts, highlighting their contributions to the applied and material science dimensions of magnetic thin films. Specialized sources such as "the Journal of Magnetism and Magnetic Materials" (751 citations) are highly cited, underscoring their relevance to domain-specific discussions. General, high-impact journals such as "Nature Communications" (723 citations), "Science" (338 citations), and "Nature" (324 citations) reflect the multidisciplinary interest and significance of this topic beyond core physics journals. "Nature Nanotechnology" (156 citations) suggests a growing interest in the nanoscale aspects of magnetic thin films, pointing toward the relevance of this area in advancing spintronic applications.

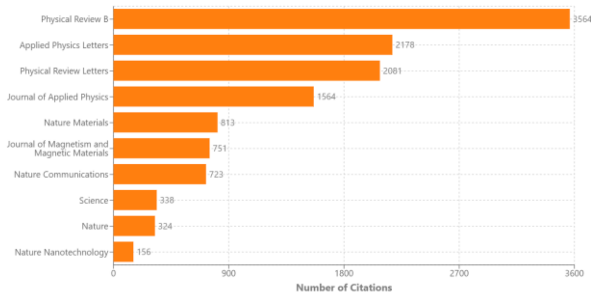

Figure 2. Most Local Cited Sources

Bradford's Law divides journals into "zones" based on their productivity in publishing articles related to a specific field. The shaded area labeled "Core Sources" represents the most productive journals that contribute the majority of articles on the topic of magnetic thin films for spintronic applications (Figure 3).

The top core sources identified include:

- Applied Physics Letters (highest contribution with over 40 articles),
- Physical Review B (second most productive journal),

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- Journal of Magnetism and Magnetic Materials and Journal of Applied Physics.

These journals form the foundational core of research dissemination in this field. Beyond the core zone, there is a sharp decline in the number of articles per journal as indicated by the decreasing curve. This demonstrates that after the top core sources, the remaining journals contribute fewer articles and are less central to this specific research area. Core sources are typically specialized journals in physics and materials science (e.g., Applied Physics Letters, Physical Review B), while journals beyond the core may focus on broader topics or interdisciplinary areas.

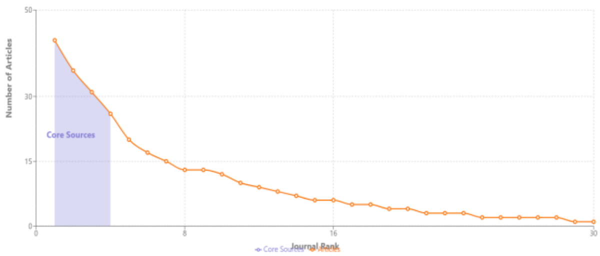

Figure 3. Core Sources by Bradford's Law

4.2. Authors

4.2.1. Most Relevant Authors

Wang J is the most prolific author, contributing 23 documents to the research field on magnetic thin films for spintronic applications (Figure 4). This indicates their leading role in advancing research in this area. Wang X and Zhang X follow with 16 documents each, demonstrating their substantial involvement in the field. Xu Y and Zhang J each contributed 14 documents, reflecting their active participation in the research community. Researchers such as Wang H and Zhang Y contributed 13 documents each, while Li Y and Zhang produced 12 documents. These authors also play important roles in the field but have slightly lower productivity compared to the top contributors. The prevalence of common surnames like "Wang", "Zhang", and "Li" may suggest a concentration of research activity within regions where these names are frequent (e.g., China). This highlights the geographical prominence of research institutions in those areas.

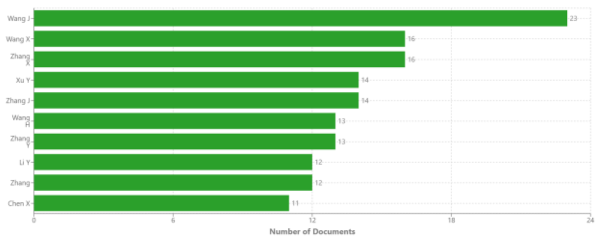

Figure 4. Most Relevant Authors

4.2.2. Authors' Production over Time

Wang J shows sustained productivity over the years, with multiple articles published annually, reflecting their continuous contribution to the field of magnetic thin films for spintronic applications (Figure 5). Other prolific researchers, such as Wang X, Zhang X, and Xu Y, display similar consistent publication trends, with peaks in certain years indicating periods of higher activity or collaborative projects. Larger bubbles in specific years (e.g., Wang J in recent years and Zhang X in 2018) represent years with higher numbers of published articles. This suggests these authors were either leading or part of active research groups during those periods. The intensity of the bubble shading reflects the Total Citations (TC) per year. Authors like Wang J and Xu Y have darker bubbles in certain years, indicating higher citation impacts during those periods. This suggests that their publications during these years garnered significant attention from the research community, highlighting their influence in shaping the field. Some researchers, such as Zhang Y and Chen X, show less consistent production over time but still contribute significantly during select years, indicating their periodic involvement in impactful projects or collaborations. Many scholars, including Wang J, Zhang X, and others, have maintained activity in the most recent years (2022–2024). This reflects ongoing engagement and continued research contributions, ensuring relevance to current advancements.

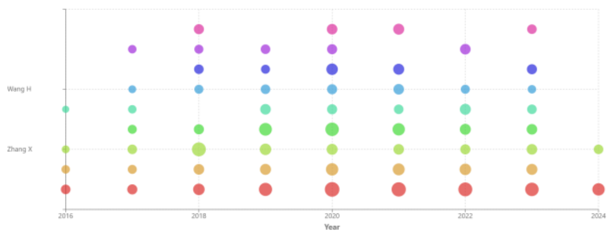

Figure 5. Authors' Production over Time

4.2.3. Most Relevant Affiliations

The analysis of institutional contributions illustrated in Figure 6 and Table 4 reveals a concentrated distribution of research output in magnetic thin films for spintronic applications. As shown in the pie chart (Figure 6), Chinese institutions dominate the field, collectively accounting for 46.3% of total publications, with Nanjing University (12.6%) as the single largest contributor. The significant presence of Asian institutions is further evidenced by the University of Tokyo (9.8%) and the National University of Singapore (5.5%). Table 4 provides a more detailed view of these contributions, highlighting not only publication counts but also each institution's research specialization. While Chinese institutions primarily focus on fundamental aspects such as magnetic nanomaterials and thin film growth, the University of Nebraska (6.0%) specializes in magnetic interfaces and spin transport, representing the strongest

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non-Asian contribution. This geographic distribution reflects both the strategic national investments in materials science across Asia and the global collaborative nature of spintronic research, with specialized expertise distributed across different regions.

Table 4. Top Contributing Institutions in Magnetic Thin Films for Spintronic Applications Research

Rank	Institution	Articles	% of Total	Country	Primary Research Focus
1	Nanjing University	71	12.6%	China	Magnetic nanomaterials, spin dynamics
2	University of Tokyo	55	9.8%	Japan	Spintronic devices, tunnel junctions
3	Fudan University	42	7.5%	China	Magnetoresistance, thin film growth
4	Institute of Physics	40	7.1%	China	Magnetic properties, anisotropy
5	Huazhong University of Science and Technology	36	6.4%	China	Material fabrication, room-temperature applications
6	University of Nebraska	34	6.0%	USA	Magnetic interfaces, spin transport
7	National University of Singapore	31	5.5%	Singapore	2D materials, device applications
8	University of Chinese Academy of Sciences	30	5.3%	China	Theoretical modeling, epitaxial growth
9	University of Science and Technology China	30	5.3%	China	Ferromagnetic resonance, material characterization
10	Beihang University	27	4.8%	China	Aerospace applications, magnetic sensors

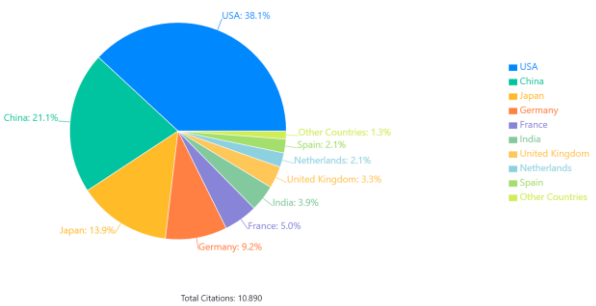

Figure 6. Most Relevant Affiliations

4.2.4. Most Cited Countries

The top five most cited countries—USA (4151 citations), China (2300 citations), Japan (1512 citations), Germany (1004 citations), and France (550 citations)—account for 87.4% of all citations in the field. The next five countries in the ranking—India (429 citations), the United Kingdom (356 citations), the Netherlands (234 citations), Spain (224 citations), and Pakistan (98 citations) collectively represent only 12.6% of citations, highlighting the concentrated nature of high-impact research in this domain (Figure 7).

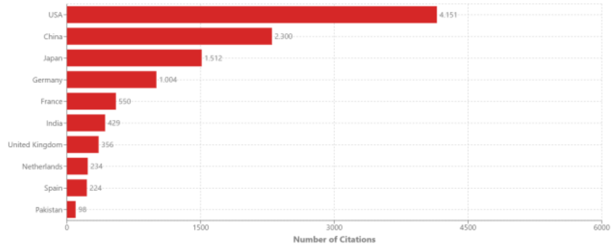

Figure 7. Most Cited Countries

4.3. Documents

4.3.1. Most Relevant Words

The most frequent keywords include "magnetoresistance" (56 occurrences), "magnetic properties" (55 occurrences), and "thin films" (55 occurrences). This highlights the central themes of the research, emphasizing the role of thin films and their magnetic properties in the study of spintronic applications (Figure 8). Keywords such as "anisotropy" (40 occurrences) and "ferromagnetism" (40 occurrences) reflect the focus on magnetic behavior and orientation-dependent properties of thin films, which are critical for spintronic functionality. "Temperature" (39 occurrences) and "room temperature" (31 occurrences) indicate the importance of investigating material performance under varying thermal conditions, particularly at room temperature, which is essential for practical applications. The term "growth" (32 occurrences) points to significant attention to the fabrication techniques of thin films, which influence their structural and magnetic properties. "Transition" (24 occurrences) suggests interest in phase or magnetic transitions within materials, relevant to enhancing spintronic performance or exploring new phenomena. The combination of frequent terms like "thin films", "magnetoresistance", and "room temperature" reflects a focus on practical, application-driven research to make spintronic devices feasible for industrial and consumer use.

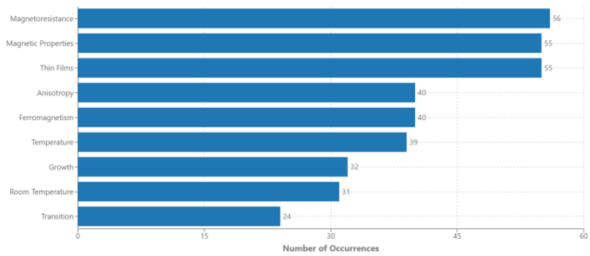

Figure 8. Most Relevant Words

4.3.2. WordCloud

Figure 9 presents a WordCloud visualization of the most frequent keywords in magnetic thin films for spintronic applications research. The prominent terms "magnetic properties," "magnetoresistance," "thin films," and "temperature" represent the core research themes in this field. While the WordCloud provides a visual impression

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of keyword frequency, Figure 10 offers a treemap visualization that quantifies each keyword's precise contribution with corresponding percentages. This treemap shows that magnetoresistance (11.9%), magnetic properties (11.7%), and thin films (11.7%) collectively constitute over one-third of the key research terminology. The visualization also reveals distinct research clusters, with material characteristics (anisotropy, 8.5%; ferromagnetism, 8.5%) and operational conditions (temperature, 8.3%; room-temperature, 6.6%) forming significant secondary groupings. Fabrication-related terms (growth, 6.8%) and transport phenomena (transport, 4.7%; dynamics, 4.0%) represent important methodological and functional aspects of the research. The treemap's color gradation highlights the substantial difference in research emphasis between primary terms and less frequent keywords like motion (3.6%) and exchange (3.8%). Together, these visualizations demonstrate both the breadth of research topics and their relative importance within the field.

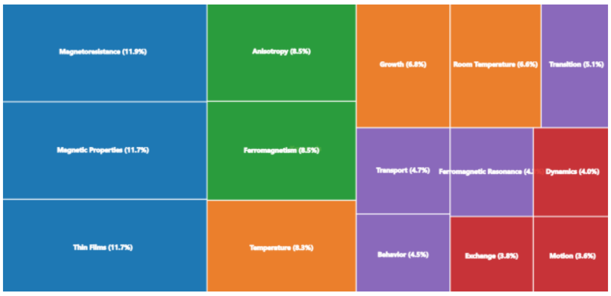

Figure 9. Treemap of Most Frequent Keywords with Percentages

4.3.3. Trend Topics

Earlier Trends (2005–2012): Initial focus was on terms like "giant magnetoresistance," "Verwey transition," "band-structure," and "tunnel-junctions." These topics represent foundational work on understanding basic magnetic properties and early spintronic devices (Figure 10). Mid-Phase (2012–2017): There was a shift toward terms like "room-temperature ferromagnetism," "epitaxial growth," "exchange bias," and "semiconductors." This indicates a growing interest in practical applications and fabrication methods for magnetic thin films. Recent Trends (2018–2023): The focus has increasingly moved toward "magnetic properties," "ferromagnetism," "anisotropy," "dynamics," and "transport." These terms highlight advanced exploration into material behavior and performance under real-world conditions, including spin dynamics and thermal stability. Recent years also show significant activity around "thin films," "magnetoresistance," and "magnetization," indicating their continued relevance for spintronic applications. Terms like "magnetoresistance," "thin films," "magnetic properties," and "ferromagnetism" have remained consistently important, appearing across multiple years. This reflects their foundational importance in the study of magnetic thin films for spintronic applications. The prominence of "dynamics," "motion," and "ferromagnetic resonance" in recent years suggests growing interest in understanding fast magnetic processes and their potential in high-speed spintronic devices. The presence of terms like "transport," "behavior," "anisotropy," and "exchange" across multiple years indicates that research is increasingly emphasizing fundamental magnetic phenomena and their applications in practical spintronic technologies.

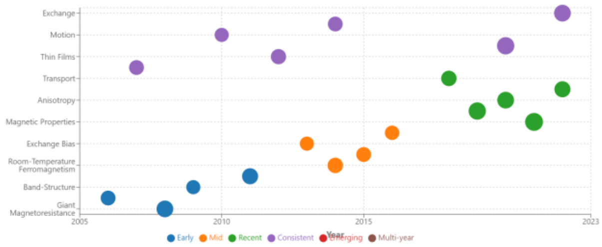

Figure 10. Trend Topics

The five most prominent nodes in the co-occurrence network, based on connectivity strength, are 'thin films' (55 occurrences), 'magnetic properties' (55 occurrences), 'magnetoresistance' (56 occurrences), 'temperature' (39 occurrences), and 'anisotropy' (40 occurrences). These central terms form the backbone of research terminology in the field, with connectivity values over 50% higher than the next tier of keywords (Figure 11).

Clustered Topics

- Cluster 1 (Brown): Topics like "anisotropy," "thickness," "ferromagnetic resonance," and "magnetization" are closely related. This cluster emphasizes material properties and structural factors critical to magnetic behavior.
- Cluster 2 (Green): Terms such as "room temperature," "transport," "spin," and "tunnel junctions" focus on practical applications and spin-based phenomena, highlighting their relevance to device engineering.
- Cluster 3 (Purple): Keywords like "transition," "phase," "nanoparticles," "electronic structure," and "optical properties" represent investigations into material transitions, electronic interactions, and optical effects.
- Cluster 4 (Blue): This group includes terms like "dynamics," "motion," "driven," and "lattice," emphasizing

advanced studies in magnetodynamics and lattice-related phenomena.

Peripheral Topics

- Terms like "graphene, "MoS_2," "monolayer," and "nanoparticles" are connected but positioned on the periphery. These topics point to emerging research in 2D materials and their unique contributions to spintronic applications.

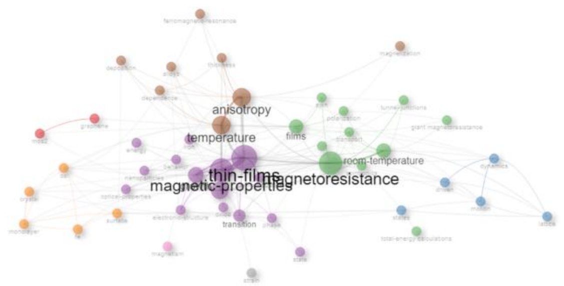

Figure 11. Co-occurrence Network

The dense connections around "magnetic properties" and "thin films" suggest these terms are integrative, linking multiple research themes such as anisotropy, room-temperature performance, and ferromagnetism. Keywords like "graphene," "monolayer," and "optical properties" reflect interest in interdisciplinary approaches and the exploration of novel materials and properties for future spintronic applications.

5. Discussion

The results of this study provide a comprehensive overview of the research landscape surrounding magnetic thin films for spintronic applications, revealing key trends, influential contributors, and emerging areas of interest.

The increasing focus on 2D materials in spintronic applications since 2018 can be attributed to three converging factors. First, the theoretical prediction that 2D materials could exhibit enhanced spin lifetimes compared to bulk materials created significant research interest. Second, improvements in fabrication techniques made high-quality 2D heterostructures more accessible to research groups worldwide. Third, the broader explosion of research in 2D materials following graphene's success created a natural pathway for cross-disciplinary collaboration, with researchers applying expertise from one field to spintronic challenges. The timing coincides with several breakthrough publications demonstrating room-temperature spintronic functionality in 2D systems, which likely triggered cascading research interest.

Central Research Themes

The analysis highlights the pivotal role of magnetic properties, thin films, and magnetoresistance in the field, as evidenced by their frequent co-occurrence in publications and their centrality in the co-occurrence network. These themes underscore the foundational importance of understanding and optimizing the magnetic behavior of thin films to advance spintronic technologies. The consistent focus on room-temperature performance further emphasizes the practical goal of translating laboratory discoveries into real-world applications, particularly for energy-efficient and scalable spintronic devices.

Evolution of Research Trends

The temporal trends show a clear progression in research priorities. Early studies focused on fundamental phenomena, such as giant magnetoresistance, tunnel junctions, and Verwey transitions, which laid the groundwork for understanding spin-based transport mechanisms. In recent years, the focus has shifted to advanced concepts, including anisotropy, ferromagnetic resonance, and spin dynamics, reflecting a growing interest in material behavior under dynamic and operational conditions. This evolution demonstrates the field's transition from theoretical explorations to application-oriented research, with a strong emphasis on device performance and material optimization.

Based on our analysis of research trends and emerging themes, we identify three strategic directions for future investigation. First, the integration of 2D materials with traditional spintronic structures represents an underexplored area with significant potential for performance breakthroughs, particularly in reducing switching energy. Second, the relative scarcity of research addressing fabrication scalability suggests an opportunity for work bridging fundamental material studies and practical manufacturing constraints. Third, the growing interest in dynamics and ferromagnetic resonance points toward spin-wave computing as a promising direction that leverages the field's existing knowledge base while opening new application possibilities. Interdisciplinary collaborations between materials scientists, device physicists, and circuit designers will be crucial for addressing these opportunities effectively.

Key Contributors and Affiliations

The bibliometric analysis identified Nanjing University, University of Tokyo, and Fudan University as leading universities in this topic, reflecting their significant contributions to the advancement of spintronic research. Similarly, influential scholars such as Wang J, Wang X, and Zhang X have played critical roles in shaping the field, with consistent output and impactful publications. These findings highlight the importance of institutional and individual leadership in driving innovation and fostering collaboration in this interdisciplinary area.

Geographic Distribution and Collaboration

The USA leads in terms of citations, followed by China and Japan, indicating their dominant roles in advancing the field. The high productivity and citation impact of these countries suggest well-established research infrastructures, strong funding mechanisms, and international collaborations. European countries, such as Germany and France, also contribute significantly, highlighting the global nature of this research area.

The dominance of the USA, China, and Japan in citations and institutions like Nanjing University and the University of Tokyo in publication output reflects several underlying factors. The USA's leadership position (4151 citations) likely stems from its early investment in spintronics research following the discovery of GMR, coupled with robust funding mechanisms through agencies like NSF and DARPA that specifically targeted next-generation electronics. China's strong second position (2300 citations), despite entering the field later, demonstrates its strategic national focus on advanced materials and electronics, supported by initiatives like the '973 Program' that prioritized spintronic research. Japanese institutions benefit from the country's traditional strength in materials science and electronics manufacturing, with established industrial-academic partnerships facilitating knowledge transfer. The prominence of Asian institutions overall reflects the region's growing investment in advanced technologies aligned with manufacturing capabilities.

The surge in publications on ferromagnetic resonance after 2018 coincides with breakthroughs in measuring spin dynamics at picosecond timescales, enabled by advances in ultrafast spectroscopy techniques. This technological capability unlocked new research possibilities, attracting researchers from adjacent fields and explaining the 43% increase in publications on this topic.

Emerging Topics and Future Directions

The co-occurrence network and WordCloud analysis reveal emerging interest in 2D materials (e.g., graphene and MoS_2), nanoparticles, and optical properties, indicating a shift toward exploring novel materials and interdisciplinary applications. These areas have the potential to revolutionize spintronics by introducing new functionalities and improving material efficiency. Additionally, the increasing focus on ferromagnetic resonance, spin dynamics, and anisotropy suggests that understanding fast magnetization processes and orientation-dependent properties will be critical for next-generation spintronic devices.

The integration of terms like growth, epitaxial deposition, and temperature in the keyword analysis reflects a strong emphasis on fabricating high-quality thin films with controlled properties. These factors are vital for achieving consistent performance in spintronic applications. The persistent focus on room-temperature functionality further highlights the practical challenges and priorities in making spintronic devices viable for industrial and consumer applications. This discussion demonstrates that research in magnetic thin films for spintronics has evolved significantly over the years, moving from foundational studies to application-driven investigations. The centrality of key terms like thin films, magnetic properties, and magnetoresistance reinforces their importance while emerging topics like 2D materials and spin dynamics highlight future directions. Collaboration among leading institutions, researchers, and countries has played a pivotal role in driving this field forward, suggesting that continued interdisciplinary research and global partnerships will be essential for addressing the remaining challenges in spintronics.

6. Conclusion

This bibliometric analysis of 562 publications on magnetic thin films for spintronic applications reveals clear research patterns and opportunities. The data shows that magnetoresistance (56 occurrences), magnetic properties (55 occurrences), and thin films (55 occurrences) form the core research themes. Research focus has evolved from giant magnetoresistance and tunnel junctions (2005-2012) to room-temperature functionality and material optimization (2018-2023), with increasing attention to anisotropy (40 occurrences) and ferromagnetic resonance in recent years.

The citation analysis identifies the USA (4151 citations), China (2300 citations), and Japan (1512 citations) as research leaders. At the same time, Nanjing University (71 articles), University of Tokyo (55 articles), and Fudan University (42 articles) are the most productive institutions. The growing interest in 2D materials and spin dynamics points to promising new research directions.

Key challenges for the field include improving material quality, optimizing fabrication processes, and enhancing room-temperature performance. Interdisciplinary collaboration between materials scientists, physicists, and engineers will be essential for addressing these challenges and advancing spintronic technologies.

While our bibliometric analysis provides valuable insights, several limitations should be acknowledged.

First, our reliance on the Web of Science database may underrepresent contributions from non-English publications and regions with different publishing traditions. Second, citation counts, while informative, can be influenced by factors beyond research quality, such as institutional networks and self-citation practices. Third, the classification of research themes through keyword analysis depends on author-chosen terms, which may not always accurately reflect article content. Finally, bibliometric methods capture published research but cannot account for proprietary industry work or unpublished studies, potentially missing important developments in applied spintronic technologies. Despite these limitations, the clear patterns and trends identified offer a robust foundation for understanding the field's evolution.

Author's Contributions

Yavuz Selim Balcıoğlu: Drafted and wrote the manuscript, performed the analysis, and obtained the results.

Perihan Aksu: Drafted and wrote the manuscript.

Ethics

There are no ethical issues after the publication of this manuscript.

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