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Bibliometric Analysis of Global Research Trends on Simulation Studies of AlGaN/GaN High-Electron-Mobility Transistors Using the Scopus Database

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Bibliometric Analysis of Global Research Trends on Simulation Studies of AlGaN/GaN High-Electron-Mobility Transistors Using the Scopus Database

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Abstract

This study presents a bibliometric analysis of global research trends on simulation studies of AlGaN/GaN high-electron-mobility transistors (HEMTs) using the Scopus database. Despite the growing reliance on simulation for device physics and performance prediction, a comprehensive global overview of this specific research area has been lacking. A total of 4,492 journal articles and conference papers published between 1997 and 2026 were retrieved and analyzed. The results reveal a rapid and sustained growth in publication output, with China, India, and the United States being the most productive countries. The University of Electronic Science and Technology of China and Xidian University emerged as leading institutions, while IEEE Transactions on Electron Devices was the most prolific journal. Keyword co-occurrence analysis identified six major research clusters, including power and thermal management, device modeling, radio frequency (RF) applications, and Technology Computer-Aided Design (TCAD) simulation. Furthermore, application trends indicate a recent shift toward power electronic switching converters. This analysis provides researchers and policymakers with a comprehensive understanding of the current landscape and potential future directions in AlGaN/GaN HEMT simulation research.

Keywords: AlGaN/GaN HEMT, Simulation, Bibliometric analysis, Scopus database, Research trends

1 Introduction

Wide-band-gap (WBG) semiconductors are defined as semiconductors with energy gaps between 3.2 and 3.4 eV, which have attracted the attention of researchers due to the widespread applications of materials science and devices with the significant efficiency they can provide [1]. Because increasing the band energy increases the breakdown avalanche electric field [2], this fact places WBG semiconductors as the best solution for high-field, high-power electronics, long-range telecommunications, electric vehicles, and other applications. Among the different WBG semiconductors, aluminium gallium nitride (AlGaN) and its heterostructure with gallium nitride (GaN) have emerged as leading material systems for high-power and high-frequency applications. In particular, the AlGaN/GaN high-electron-mobility transistor (HEMT) exploits the two-dimensional electron gas (2DEG) formed at the heterointerface, providing high electron mobility, high breakdown voltage, and excellent thermal stability [3]. These properties make AlGaN/GaN HEMTs a preferred choice for next-generation power electronics, RF amplifiers, and harsh-environment devices [4].

As the design space of AlGaN/GaN HEMTs grows increasingly complex, simulation has become an indispensable tool for understanding device physics, optimizing layer structures, and predicting performance before fabrication. Technology Computer-Aided Design (TCAD), two-dimensional device simulators, and physics-based models are now widely used to study effects such as trap dynamics [5], self-heating, breakdown behavior, and current collapse [6]. Despite this growing reliance on simulation, very few studies have been dedicated to measuring and analyzing the scientific publications on AlGaN/GaN HEMT simulation from a global perspective. Rajan and Li [7] presented research progress on WBG semiconductors, where AlGaN/GaN devices were part of the discussion. However, their study was limited to a specific scope and did not provide a comprehensive bibliometric analysis of simulation-focused research on AlGaN/GaN HEMTs. Scopus is recognized as the largest abstract and citation database of peer-reviewed literature, covering a wide range of subjects and indexing more journals than other databases [8]. Thus, using Scopus is an attempt to cover more topics which may not be available in other databases and may not have been discussed by previous studies.

In this paper, our objectives were as follows: (i) to analyze the temporal distribution patterns of simulation-based journal articles on AlGaN/GaN HEMTs; (ii) to show the contributions of prolific authors, leading countries, and the most productive academic institutions; (iii) to highlight common terminology and research topics in simulation studies; (iv) to determine the dominance of countries based on simulation-focused research; and (v) to provide insight into potential collaboration and future directions. This paper will be beneficial for researchers, policy makers, and individuals to understand the research trends in AlGaN/GaN HEMT simulation and to discover the potential and opportunities for future research.

2 Methods

Bibliometric analysis is a mechanistic approach to understanding global research trends in a specific area based on the outputs of an academic literature database.

This kind of approach distinguishes a bibliometric analysis paper from a review paper, which primarily intends to discuss the latest progress, challenges, and future directions of a certain topic.

2.1 Data source and search strategy

Data mining was conducted between September 29 and October 5, 2026, using the Scopus database, the largest abstract and citation database of peer-reviewed literature [8]. The publication cutoff was October 1, 2026. The central theme of this study was simulation-based research on AlGaN/GaN high-electron-mobility transistors (HEMTs). The oldest publication dates to 1997, and the most recent ones are from 2026. The Scopus query used for the search was:

```
(ALL(algan gan) AND TITLE-ABS-KEY(hemt) AND ALL(simulation))
AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"cp"))
AND (LIMIT-TO(SUBJAREA,"ENGI") OR LIMIT-TO(SUBJAREA,"MATE")
OR LIMIT-TO(SUBJAREA,"PHYS") OR LIMIT-TO(SUBJAREA,"COMP")
OR LIMIT-TO(SUBJAREA,"MATH") OR LIMIT-TO(SUBJAREA,"ENER"))
AND PUBYEAR > 1996 AND PUBYEAR < 2027
```

The central thematic block `(ALL(algan gan) AND TITLE-ABS-KEY(hemt) AND ALL(simulation))` returned 4,723 records. These were then refined in two successive steps. First, the search was restricted to six subject areas—Engineering, Materials Science, Physics and Astronomy, Computer Science, Mathematics, and Energy—which reduced the set to 4,686 records. This restriction was applied to focus on the simulation and device-physics literature and to exclude records in which the term HEMT appears as an unrelated acronym in medical, agricultural, or social-science contexts. While this subject-area filter was applied, it should be noted that we did not manually screen every abstract; therefore, some peripheral papers mentioning the search terms in passing may remain in the dataset. Second, the document type was limited to articles and conference papers, which excluded books, review papers, and conference reviews, and yielded a final analyzed set of 4,492 records. The publication-year window (1997–2026) was enforced directly within the query via the `PUBYEAR` constraint. The complete record-collection and screening process is summarized in Fig. 1.

The final set of 4,492 records was published across 2,932 distinct journals and conference proceedings. The search results were analyzed according to source, author, affiliation, country/territory, subject area, and document type. Indicators such as total publications, total citations, CiteScore, and h-index were used for ranking purposes. All retrieved records were exported in CSV format for downstream bibliometric and network analysis, as described in the following subsections.

2.2 Analysis of co-authorship

In the analysis of co-authorship, we included all countries affiliated with the retrieved authors. The affiliated countries/territories were clustered into five continents: Africa, America, Asia, Europe, and Oceania. The link strength between countries indicates the number of publications that two affiliated countries have co-authored, whereas the total link strength indicates the total strength of the co-authorship links of a given country with other countries.

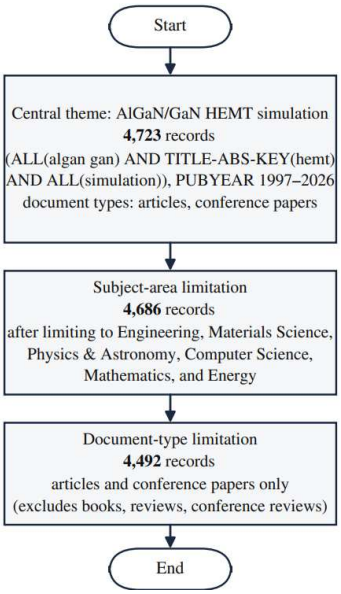

Fig. 1 Flowchart of the data collection and screening process for the central theme.

2.3 Analysis of co-occurrence

Analysis of co-occurrence of author keywords (not a Scopus-indexed keyword) involved 2,800 raw keyword entries from 4,000 of the 4,492 articles. The remaining 492 articles were excluded because author keyword information was not available for them in 140 journals. After merging synonymous single words and congeneric phrases (for example, finite element analysis, finite element method, finite element simulation, and finite element modeling were all counted as "DFT"), the number of unique keywords was reduced to 561. Of these, 61 keywords met the minimum occurrence threshold of 5 and were used for mapping in VOSviewer.

In VOSviewer, the minimum occurrences of a keyword to be analyzed is set to 5. The overlay visualization mode was selected to view the average publication year, the number of occurrences, and the link strength of the keyword. The color of a keyword indicates the average publication year of the documents in which a keyword occurs.

2.4 AlGaN applications

The trends of search outputs between the central theme (keyword co-occurrence) and sub-theme (total publication) were compared. For example, if AlGaN alloys are the application, then the VOSviewer software keywords for AlGaN and alloy were all counted. We also analyzed the five countries with the highest number of publications for each AlGaN application.

3 Results and discussion

3.1 Publication output and growth of research interest

For a period of 30 years (1997–2026), a total of 4,492 research articles had been published (Fig. 2). The oldest publication date was 1997 with 2 articles, and there was no other publication record until 1998 (2 articles). It is suggested that a strong interest in AlGaN/GaN HEMT simulation research started from 2001. In 2002, the annual growth rate (AGR) increased by 500%, and it doubled in 2006 and 2008. Since then, the annual publication count has increased steadily, resulting in a rapid increase in the cumulative total of publications. It was also found that the number of publications increased by 100 every couple of years. The highest annual output was recorded in 2025 with 490 articles, followed by 451 in 2024 and 403 in 2026 (partial year, with data collected through October 1, 2026). Therefore, it is anticipated that the annual publications will continue to increase.

While the absolute number of publications has grown rapidly, we acknowledge that this growth may partly reflect the general expansion of global scientific publishing. A direct normalization against the broader field of semiconductor simulation was not performed in this study, which is a limitation of our analysis. Therefore, the observed trends should be interpreted as absolute growth in the sub-field rather than a definitive measure of relative share of attention.

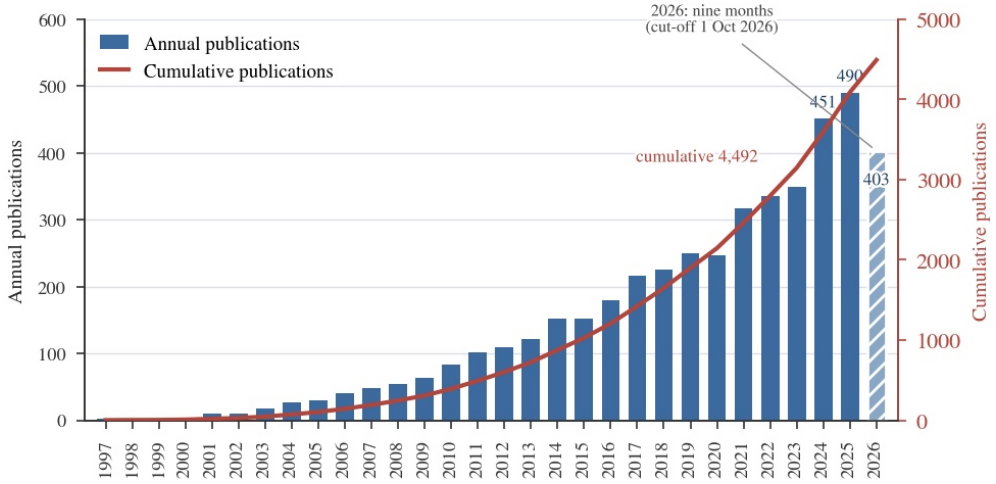

Fig. 2 The annual and cumulative numbers of research articles on AlGaN/GaN HEMT simulation indexed in Scopus from 1997 until 2026.

Most of these articles are not freely available, and users must pay to access the information in them. The best way to increase the citations within an article, as we suggested, is to publish it in open-source journals. In 2024, fewer than 500 articles were published as open-access articles.

AlGaN/GaN HEMT simulation research is extensive, and many research groups worldwide are actively working in this field. Analysis based on the subject area showed that physics and astronomy are the primary focus in AlGaN/GaN HEMT studies. This is evidenced by the total publications classified under the following subject areas: Physics and Astronomy (2,776 articles), Materials Science (2,628 articles), Engineering (2,364 articles), Chemistry (448 articles), and Computer Science (223 articles). It is clear that AlGaN/GaN HEMT simulation is a multidisciplinary area, and one of the publications was categorized under business management and accounting. AlGaN was attractive for a business management approach at Shanghai Electric Power University, Shanghai, China, by Gao Zhongze, Tang Naiyun, Cao, and Wei [9]. This kind of approach can be used to increase the financial funding for developing fourth-generation semiconductors based on wide-band-gap semiconductors and to enhance the fast transition to new technology based on fresh narratives around functional research.

Results also showed that the articles used in this study were published in five different languages: English, Chinese, Korean, Japanese, and Russian. Note that when an article is published in Scopus, the article should have a title and abstract in English, and this makes it the major feature of articles published in English, with more than 90% of the total language articles.

3.2 Preferred journals

Our results showed that the top 10 most productive journals are owned by five different publishers (Table 1). IEEE dominates the list with three journals (ranks 1, 4, and 5), followed closely by Elsevier with three journals (ranks 3, 6, and 8). The remaining four journals are published by IOP Publishing (rank 2), MDPI (rank 7), AIP Publishing (rank 9), and Wiley (rank 10).

The most productive journal was *IEEE Transactions on Electron Devices* with 353 articles, covering 7.86% of the total publications. This journal also accumulated the highest total citations (14,355), highlighting its central role in the field. It was followed by *Semiconductor Science and Technology* (103 articles, 2.29%), *Microelectronics Reliability* (84, 1.87%), *IEEE Electron Device Letters* (83, 1.85%), *IEEE Transactions on Microwave Theory and Techniques* (79, 1.76%), *Solid State Electronics* (74, 1.65%), *Micromachines* (74, 1.65%), *Microelectronics Journal* (74, 1.65%), *Applied Physics Letters* (62, 1.38%), and the *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields* (57, 1.27%).

According to the CiteScore 2026 report, the journals with the highest CiteScore among the top 10 were *IEEE Electron Device Letters* and *IEEE Transactions on Microwave Theory and Techniques* (both at 7.4), followed by *Micromachines* (7.3), while *Solid State Electronics* had the lowest at 2.9. Furthermore, we also understand that the literature can influence the decision of some authors to select journals that fit their most novel and significant work. The Elsevier-Scopus alternative to the Clarivate Analytics impact factor is a metric for measuring journal impact based on citation data from the Scopus database. In our opinion, however, CiteScore should not be taken as the only measurement. Besides it, authors should also consider whether the journal can deliver the work to the right audience and contribute to the progress of

the field. To support our fellow researchers in finding possible journals to submit their AlGaN-related work, we have listed the top 30 CiteScore journals in Table S2.

Table 1 Top 10 Most Productive Journals in AlGaN/GaN HEMT Simulation Research. TP: Total Publications; TC: Total Citations of the analyzed corpus.

Rank	Journal	TP (%)	TC	CiteScore	The Most Cited Article	Times Cited	Publisher
1	IEEE Trans. Electron Devices	7.86%	14,355	6.0	Trapping effects and microwave power performance in AlGaN/GaN HEMTs	648	IEEE
2	Semicond. Sci. Technol.	2.29%	1,148	3.6	Numerical simulation of current-voltage characteristics of AlGaN/GaN HEMTs at high temperatures	55	IOP Publishing
3	Microelectron. Reliab.	1.87%	1,536	4.5	Electro-thermal modeling of multifinger AlGaN/GaN HEMT device operation including thermal substrate effects	110	Elsevier
4	IEEE Electron Device Lett.	1.85%	3,465	7.4	P-GaN Gate HEMTs with tungsten gate metal for high threshold voltage and low gate current	299	IEEE
5	IEEE Trans. Microw. Theory Techn.	1.76%	3,650	7.4	GaN microwave electronics	258	IEEE
6	Solid-State Electron.	1.65%	1,539	2.9	High-temperature modeling of AlGaN/GaN HEMTs	153	Elsevier
7	Micromachines	1.65%	710	7.3	Optimization AlGaN/GaN HEMT with Field Plate Structures	47	MDPI
8	Microelectron. J.	1.65%	692	3.7	Thermal model for dc characteristics of AlGaN/GaN HEMTs including self-heating effect and non-linear polarization	75	Elsevier
9	Appl. Phys. Lett.	1.38%	1,379	5.6	Thermal characterization of polycrystalline diamond thin film heat spreaders grown on GaN HEMTs	149	AIP Publishing
10	Int. J. Numer. Model.	1.27%	611	4.0	An efficient parameter extraction method for GaN HEMT small-signal equivalent circuit model	60	Wiley

3.3 Leading countries, top institutions, and international collaboration

Fig. 3 shows the geographical distribution of the top 15 most productive countries in AlGaN/GaN HEMT simulation research, while Fig. 4 shows the co-authorship network of the same countries. The size of each node in the network map is proportional to the number of publications, and the thickness of the connecting lines indicates the strength of co-authorship links between countries. The map reveals a highly connected global research community dominated by a few key players, with China and India appearing

as the two largest nodes, followed by the United States, France, Italy, Japan, and the United Kingdom.

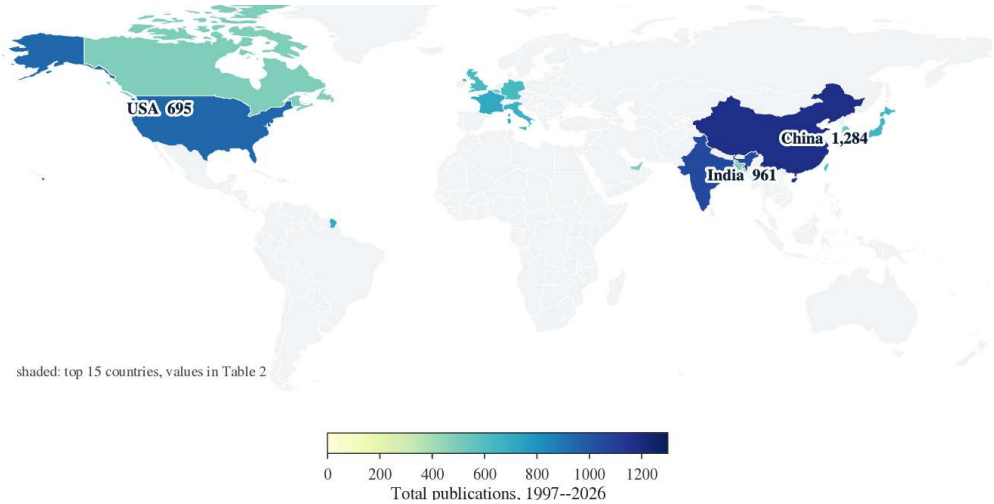

Fig. 3 Geographical distribution of the top 15 most productive countries in AlGaN/GaN HEMT simulation research. The numbers correspond to the country rankings detailed in Table 2.

About 28.6% of the global publications were contributed by China (1,284 articles), while India (961 articles, 21.4%) and the USA (695 articles, 15.5%) together accounted for nearly 37% of the global output. This indicates that these three countries are the main players in AlGaN/GaN HEMT simulation research progress. China was the leading country with 1,284 publications in a total of 188 journals. India ranked second with 961 publications, and the USA was the third most productive country with 695 publications. France (290 articles) and Italy (235 articles) follow in fourth and fifth place, respectively, while Germany (188 articles) and Taiwan (188 articles) are tied for eighth place.

The detailed breakdown of total publications, single-country publication percentages (SCP%), and the most productive academic institution for each of these 15 leading countries is provided in Table 2. The most productive academic institution globally was the University of Electronic Science and Technology of China with 174 publications, followed by the Indian Institute of Technology (146 publications), the University of Bristol (68 publications), and the University of Lille (63 publications). It is worth noting that the University of Sharjah (UAE) ranks 15th in country output but has the highest institutional concentration, with 61 of the UAE's 63 publications (96.8%) coming from a single institution.

In addition to Table 2, we also listed the 50 most productive institutions based on the number of AlGaN/GaN HEMT simulation articles. The publications of these institutions can be found in Table S3 (Supplementary Materials).

Table 2 Top 15 Most Productive Countries and Their Leading Academic Institutions in AlGaN/GaN HEMT Simulation Research. TPc: Total Publications of a given country; SCP%: Single-Country Publication percentage; TPi: Total Publications of a given institution.

Rank	Country	TPc	SCP%	Most Productive Academic Institution (TPi)
1	China	1,284	79.1%	University of Electronic Science and Technology of China (174)
2	India	961	75.0%	Indian Institute of Technology (146)
3	USA	695	58.1%	Massachusetts Institute of Technology (MIT) (55)
4	France	290	30.7%	University of Lille (63)
5	Italy	235	35.7%	University of Padua (41)
6	Japan	204	52.5%	University of Fukui (22)
7	United Kingdom	191	40.8%	University of Bristol (68)
8	Taiwan	188	39.9%	National Yang Ming Chiao Tung University (61)
9	Germany	188	33.0%	Fraunhofer Institute for Applied Solid State Physics (IAF) (61)
10	South Korea	101	30.7%	Hanyang University (8)
11	Singapore	77	10.4%	Nanyang Technological University (26)
12	Canada	71	19.7%	University of Calgary (20)
13	Belgium	69	7.2%	Interuniversity Microelectronics Center (IMEC) (45)
14	Bangladesh	67	32.8%	University of Chittagong (34)
15	United Arab Emirates	63	9.6%	University of Sharjah (61)

Note: TPc: Total Publications of a given country; SCP%: Single-Country Publication percentage; TPi: Total Publications of a given institution.

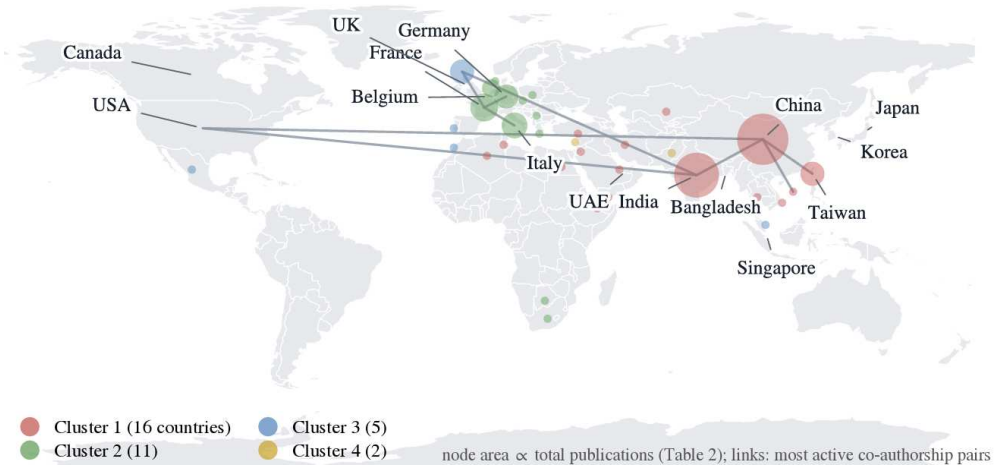

Fig. 4 Geographical distribution of co-authorship clusters. Node size indicates the number of publications, and link thickness indicates the strength of co-authorship between countries. Colors represent different clusters.

Among the 15 countries, only China (79.1%), India (75%), the USA (58.1%), and Japan (52.5%) had more than half single-country publications (SCP). This indicates a strong focus on domestic research rather than international co-authorship. It should be noted that the SCP% only measures the degree of internationalization; it does not provide information about the internal network structure or collaboration dynamics between domestic institutions. On the other hand, Belgium was the country with the least SCP, at 7.2%, where 69 publications were linked to multiple affiliations from various countries, followed by the UAE (9.6%) and Singapore (10.4%). The advantages of international collaboration are not limited to broadening the network, exchanging knowledge, and sharing expertise, but also constitute an effective strategy for ranking up. Singapore, for example, despite being a small country, has 89.6% (69 articles) of its article publications due to international collaboration, which ranks it as the 11th most productive country in this field.

The co-authorship map in Fig. 4 further reveals the structure of international collaboration. The map can be divided into four major clusters. The red cluster is the largest and includes China, India, Taiwan, Hong Kong, Macao, Iran, Thailand, Yemen, Lebanon, Jordan, Qatar, Kazakhstan, Egypt, Algeria, Djibouti, and Tunisia. The green cluster includes Germany, France, Belgium, Italy, the Netherlands, Serbia, the Czech Republic, Slovakia, Greece, South Africa, and Botswana. The blue cluster includes the United Kingdom, Mexico, Malaysia, Morocco, and Spain. The yellow cluster includes Israel, Pakistan, and South Africa. The presence of these distinct clusters suggests that geographical proximity and regional research networks play an important role in shaping collaboration patterns.

The most active collaborative links are observed between China and India, China and the USA, China and Taiwan, China and Hong Kong, India and the USA, India and the UK, and between the European countries (France, Germany, Italy, UK). The VOSviewer map also reveals that several countries have limited international links, including Macao, Lebanon, Yemen, Djibouti, Botswana, Qatar, Jordan, Greece, and Mexico. This suggests that these countries participate in the global research network only marginally, which may be attributed to smaller research communities, limited funding, or language barriers.

Several possible factors contributing to the dynamics of international collaboration can be attributed to the diversity of research partners, a high percentage of foreign postgraduates or visiting scholars, and strong research funding. It is also important to have a flexible and stable research policy to ensure the sustainability of international collaboration.

3.4 Leading authors

Table 3 lists the 10 most prolific authors in AlGaN/GaN HEMT simulation research, ranked by the number of field-specific documents each author contributed to the analyzed corpus. The authors are affiliated with five countries: India (4 authors), China (3 authors), the UAE (1 author), Australia (1 author), and Italy (1 author). Hao, Yue (Xidian University, China) leads the list with 80 field documents, followed by Ma, Xiaohua (Xidian University, China) with 68 and Jarndal, Anwar Hasan (University of Sharjah, UAE) with 67. Lenka, Trupti Ranjan (National Institute of Technology

Silchar, India) also contributed 67 documents, and the two are separated only by the secondary ordering returned by the Scopus author query. Gupta, Mridula (University of Delhi, India), Nirmal, D. (Karunya Institute of Technology and Sciences, India), Khandelwal, Sourabh (Macquarie University, Australia), Crupi, Giovanni (Università degli Studi di Messina, Italy), Saxena, Manoj (Deen Dayal Upadhyaya College, India), and Xu, Yuehang (University of Electronic Science and Technology of China, China) complete the list, with Saxena and Xu tied at 47 documents. India contributes the largest share of authors in this group (four of ten), followed by China (three), with the UAE, Australia, and Italy contributing one each. It is worth noting that the ranking by field-specific documents differs markedly from a ranking by career-wide output: for example, Hao and Ma have career totals of 2,062 and 1,623 publications respectively, whereas Jarndal and Lenka have career totals of 189 and 247 yet contributed comparable field-specific output (67 documents each). This distinction highlights that sustained specialization in AlGaN/GaN HEMT simulation, rather than overall publication volume, is what places an author among the field's most prolific contributors. Notably, Jarndal, Anwar Hasan (University of Sharjah, UAE) is the only UAE-based author in the list, consistent with the institutional concentration of UAE output at the University of Sharjah discussed in Section 3.3.

3.5 Author keywords

A total of 1,001 author keywords were recorded across the 4,168 articles for which author keyword information was available (76% of the analyzed 4,492 records). Of these keywords, 76% were used only once, 12% were used twice, and 4.6% were used three times. After relabeling synonymous single words and congeneric phrases, 561 unique keywords were retained. Of these, 61 keywords met the threshold of a minimum of 5 occurrences and were used to construct the bibliometric map in VOSviewer (Fig. 5). The resulting network consists of 61 items organized into 6 clusters, with 922 links and a total link strength of 6,060. The overlay visualization mode was used, in which the color of each keyword indicates the average publication year of the documents in which the keyword occurs (2018–2022).

3.6 Terminology and concepts

Our results showed that AlGaN was the most frequently encountered keyword, with 652 occurrences and 57 links to other keywords (Fig. 5). We also came across the use of general terms such as "HEMT," referring to "high-electron mobility transistor," with 369 occurrences and 54 links, and "GaN," referring to "gallium nitride," with 633 occurrences and 57 links. AlGaN was found to be a conceptual keyword that includes GaN and aluminum, which is the dark horse of the new mobility power characteristics [10].

The keyword co-occurrence map in Fig. 5 can be divided into six distinct clusters, each representing a major thematic area of AlGaN/GaN HEMT simulation research:

- **Cluster 1 (green, power and thermal):** breakdown voltage, current collapse, self-heating, thermal management, channel temperature, thermal resistance, reliability, trapping effect, trapping, trap states, passivation layer, and field plate.

Table 3 The 10 most prolific authors in AlGaN/GaN HEMT simulation research, ranked by the number of field-specific documents (Field Docs). Career-wide Scopus metrics (Total Publication, h-index, Total Citation) are shown for context.

Rank	Author	Scopus ID	1st Pub. Year	Field Docs	Total Pub.	h-index	Current Affiliation	Country
1	Hao, Yue	34770327100	1989	80	2,062	85	School of Microelectronics, Xidian University, Xi'an	China
2	Ma, Xiaohua	56937274100	1986	68	1,623	87	Xidian University, Xi'an	China
3	Jarndal, Anwar Hasan	9536340500	2005	67	189	24	University of Sharjah, Sharjah	UAE
4	Lenka, Trupti Ranjan	35731935800	2009	67	247	26	National Institute of Technology Silchar	India
5	Gupta, Mridula	7403986817	1996	63	448	38	University of Delhi, New Delhi	India
6	Nirmal, D.	36816416200	2010	54	201	32	Karunya Institute of Technology and Sciences, Coimbatore	India
7	Khandelwal, Sourabh	55625521800	2007	52	187	34	Macquarie University, Sydney	Australia
8	Crupi, Giovanni	57757131900	2003	48	301	34	Università degli Studi di Messina, Messina	Italy
9	Saxena, Manoj	58326833600	2002	47	274	32	Deen Dayal Upadhyaya College, New Delhi	India
10	Xu, Yuehang	23011114400	2007	47	307	62	University of Electronic Science and Technology of China, Chengdu	China

Field Docs = documents on AlGaN/GaN HEMT simulation contributed by the author in the analyzed corpus; this is the ranking criterion. Ranks 9 and 10 are tied at 47 documents and are listed in the order returned by the Scopus author query.

- **Cluster 2 (blue, device and HEMT core):** HEMT, GaN, GaN HEMT, AlGaN/GaN HEMT, AlGaN/GaN, AlGaN, p-GaN, p-GaN gate, p-GaN HEMT, p-GaN gate HEMT, normally-off, enhancement mode, threshold voltage instability, MIS-HEMT, MOS-HEMT, MOSHEMT, heterostructure, back-barrier, 2DEG, polarization charge, transconductance, linearity, biosensor, and sensitivity.
- **Cluster 3 (purple, modeling and RF):** modeling, compact model, small-signal model, large-signal model, equivalent circuit, power amplifier, power transistor, semiconductor device modeling, parameter extraction, S-parameter, simulation, MMIC, temperature dependence, and RF.
- **Cluster 4 (yellow, TCAD and gate):** TCAD simulation, gate leakage current, cut-off frequency, device studies, power device, and power electronics.
- **Cluster 5 (teal, electric field and analytical):** electric field and analytical model.
- **Cluster 6 (light green, machine learning):** artificial neural network.

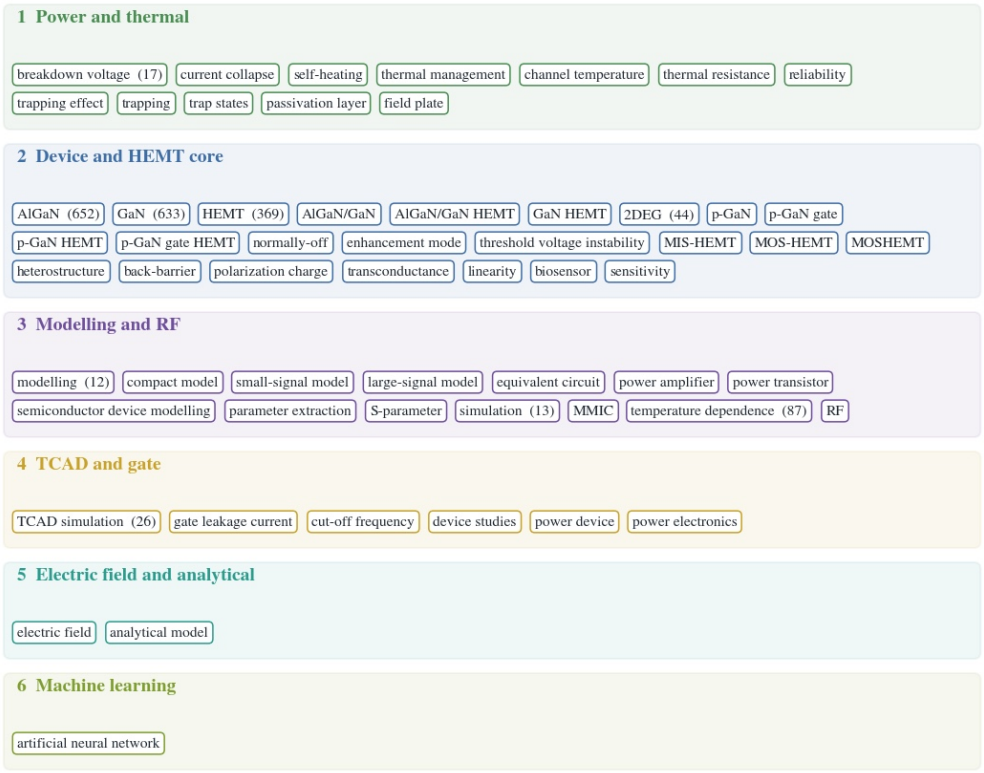

Fig. 5 A screenshot of the bibliometric map created based on author keyword co-occurrence with overlay visualization mode. The map contains 61 items grouped into 6 clusters, with 922 links and a total link strength of 6,060. The minimum occurrence of a keyword is set to five.

In addition, we noticed that several attributes, including substrate, mechanism, and configuration, were used in naming AlGaN. For example, AlGaN is associated with wide-band-gap semiconductors and extends within the wide-band-gap family (85 occurrences, 41 links), and the most notable feature of this semiconductor is its temperature dependence (87 occurrences and 41 links).

It is interesting to know how the term AlGaN was first introduced. In the early 1990s, gallium nitride (GaN) was deemed an excellent next-generation semiconductor material for high-power/high-frequency transistors based on the material parameters of bandgap, electron mobility, and saturated electron velocity. The lack of bulk GaN source material led to the need for GaN growth on mismatched substrates such as Si, SiC, and sapphire, but fundamental material development controlled the pace of maturation of GaN technology for both electronic and optoelectronic applications. The development of GaN for RF electronics was significantly aided by the intense development that occurred in the race to first production of blue and, eventually, white light-emitting diodes (LEDs). Ultimately, advancements in the growth of device-grade

aluminum gallium nitride (AlGaN)/GaN heterostructures culminated in the demonstration of record power-density RF amplifiers [11]. It is also important to mention that AlGaN materials are characterized by the high efficiency of ultraviolet-based light emitter diodes and UV emitter detectors, which are reaching rapid development, such as an electron beam (EB)-pumped AlGaN-based UV light source at 238 nm, with an output power of 100 mW and a power conversion efficiency (PCE) of 40%, which has also been fabricated [12]. These optical studies were found with 217 occurrences and 52 links, as shown in Fig. 5.

3.7 Topics of interest

As an evolving technology, AlGaN was evaluated; keywords containing the term "AlGaN" (including compound forms such as AlGaN/GaN, AlGaN barrier, and AlGaN back barrier) were repeated 1,032 times in total, compared with 652 occurrences of the standalone "AlGaN" keyword. In AlGaN research, applications, conditions, and components are the key parameters. In comparison to many semiconductors, GaN appears 1,458 times, which includes gallium nitride, GaN on silicon, GaN HEMT, and gallium oxide.

The overlay visualization in Fig. 5 further reveals the temporal evolution of research topics. Keywords colored in lighter shades (yellow) have a more recent average publication year, indicating recently active areas. However, it is important to note that recency is a mathematical average and does not guarantee long-term scientific momentum; a topic could have recently peaked and may be declining. Among the most recently active keywords are TCAD simulation, gate leakage current, and cut-off frequency (Cluster 4), as well as power amplifier, S-parameter, and large-signal model (Cluster 3). This shift in keyword frequency suggests a recent concentration of publications in simulation-driven design, RF performance, and gate reliability. In contrast, foundational keywords such as AlGaN, GaN, and HEMT (Cluster 2) have darker colors, reflecting their long-established presence in the literature.

Furthermore, the basic features of AlGaN reflect its applications. For example, the high breakdown voltage (17 occurrences), high electron mobility (109 occurrences), including high-mobility transistors and high-mobility HEMT, and high temperature (40 occurrences). One of the most famous applications of AlGaN is in light-emitting diodes (LEDs) due to the high efficiency of its heterostructures, which provide external quantum efficiency reaching more than 5% for Zn or Si co-doping into the AlGaN active layer [13]. AlGaN LEDs showed 102 occurrences. Molecular beam epitaxy and the growth parameters of AlGaN have drawn attention in the research field due to the strong interest in them, [14] results show 71 occurrences of this topic. The mechanical properties of AlGaN are of interest, especially parameters such as stress, strain, superlattice, and piezoelectricity, which showed 84 occurrences in total. AlGaN is one of the most wide-band-gap semiconductors and an extension of wide-band-gap development. Keywords that contain wide-band-gap semiconductors occurred 71 times.

Since the optical properties of AlGaN were among the most attractive for related applications, keywords containing "optical" were encountered 62 times in different phrases such as optical absorption, optical gain, optical properties, optical pumping, and optoelectronic. Solar cells are one of the products that appeared due to the growth

of band engineering of InGa multi-quantum wells using AlGaN electron-hole blocking layers. Some research discusses an increase of up to 45% in the power conversion density [15]. Keywords that include solar cell occurred 39 times.

Among the electrical parameters influencing the properties of AlGaN, consider the film grown by the deposition of metalorganic chemical vapor and the two-dimensional electron gas forming at the heterojunction [16]. Metal-organic chemical vapor deposition occurred 21 times, and two-dimensional electron gas 44 times. Following that, several strategies were employed to increase the doping efficiency of AlGaN, which is described as a difficult process compared with GaN based on results from first-principles density functional-pseudopotential calculations [17]. The "doping" keyword occurred 28 times, N-type doping 5 times, and P-type doping 23 times. This indicates that the challenge of p-type doping attracts more potential research compared with n-type doping.

Since the type of application of AlGaN could lead to a modeling approach, prediction and simulation-based studies will be useful toward scaling up the practical implementation of this technology. For example, Technology Computer-Aided Design (TCAD) has been proposed for the simulation of AlGaN/GaN MOS-HEMT for biosensor applications [18]. TCAD keywords were recognized to occur 26 times; the word "simulation" occurred 13 times, and "modeling" 12 times. The prominence of TCAD simulation and related keywords in Cluster 4 of Fig. 5 highlights the central role of simulation tools within this specific sub-field of AlGaN/GaN HEMT simulation research. It will be fascinating if many more studies include other software tools such as FDTD for applications such as DC switching or RF circuits, as demonstrated in this reference [19].

3.8 Application Trends

To characterize how the research focus on AlGaN/GaN HEMT simulation has evolved across application domains, the 4,492 analyzed records were classified into four principal application categories: (i) RF microwave power amplifiers, (ii) power electronic switching converters, (iii) device modeling and simulation using TCAD and SPICE, and (iv) thermal management. Because a single publication may address more than one application and some records fall outside these four categories (e.g., sensors and terahertz detectors), the category totals do not sum to the corpus size. Figure 6 presents the annual publication counts for each category, and Figure 7 disaggregates the leading contributing countries by application.

Device modeling and simulation (TCAD and SPICE) is the largest overall category, with **1,536** records. Its output rises steadily from a single publication in 2001 to a peak of 160 publications in 2025, reflecting the progressive maturation of physics-based and compact-modeling frameworks—surface-potential and charge-based models, large-signal and trapping-aware models, and TCAD-based electro-thermal simulations—that underpin both RF and power device design.

RF microwave power amplifiers form the second-largest category, with **1,141** records. Publications remain modest (2–15 per year) through the 2000s, when the field was dominated by proof-of-concept Class-E/Class-F and Doherty amplifiers, and then accelerate after 2015, reaching 252 records in 2025 and 262 in 2026. This growth

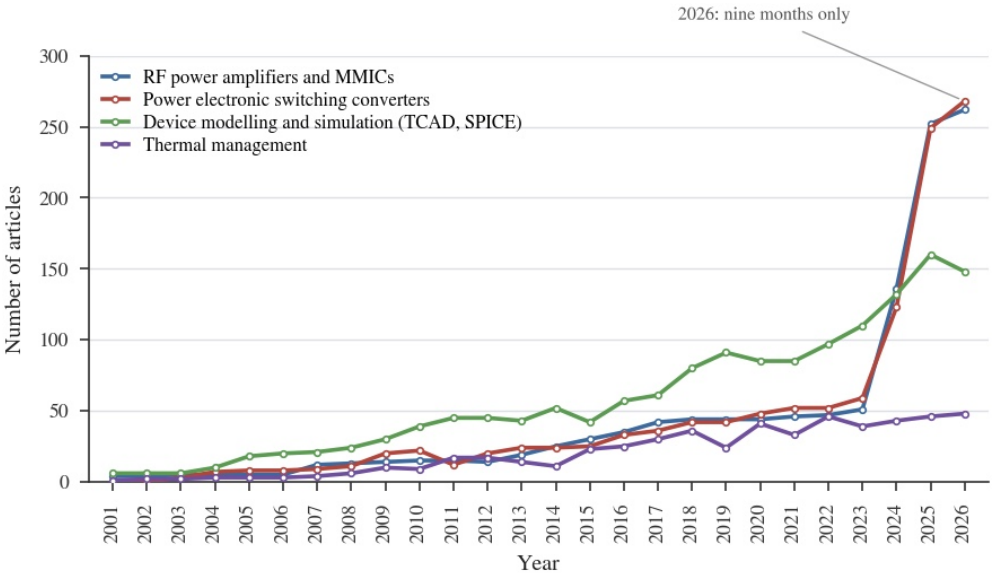

Fig. 6 Annual publication counts for the four principal application categories of AlGaN/GaN HEMT simulation research (2001–2026): RF microwave power amplifiers (1,141 records), power electronic switching converters (1,104), device modelling and simulation using TCAD and SPICE (1,536), and thermal management (518).

coincides with the migration of GaN PAs toward millimeter-wave bands, broadband architectures, and linearity/trap-aware large-signal design.

Power electronic switching converters account for **1,104** records and display the earliest sustained growth among the application categories: counts climb from 1 publication in 2001 to 20 in 2009 and 48 in 2020, before a pronounced expansion to 254 records in 2025 and 268 in 2026. This trajectory tracks the commercialization of GaN power HEMTs for high-voltage switching, and the associated literature on cascode and p-GaN gate architectures, dynamic on-resistance, gate-drive and loss analysis, and converter-level design. Notably, in the final two years of the analysis (2025–2026), power electronics overtakes RF amplifiers as the most published application, signaling a shift toward power conversion.

Thermal management is the smallest of the four categories, with **518** records, but it shows a steady, consistent upward trend. It rises from single-digit annual counts before 2009 to stabilize around 41–47 publications per year over 2020–2026. The increase reflects the centrality of self-heating and thermal-boundary resistance in high-power-density operation, and the associated work on GaN-on-diamond and GaN-on-SiC substrates, microchannel cooling, and Raman/thermoreflectance-based junction-temperature metrology.

Taken together, the four categories reveal a clear temporal shift in the field. Early work (2001–2010) was dominated by device modeling and RF PA proof-of-concept studies; the period 2010–2020 saw power-electronic switching become co-dominant with RF; and the most recent period (2020–2026) is characterized by a massive surge

in both RF and power converter publications. This diversification is consistent with the keyword-cluster structure reported in Section 3.5.

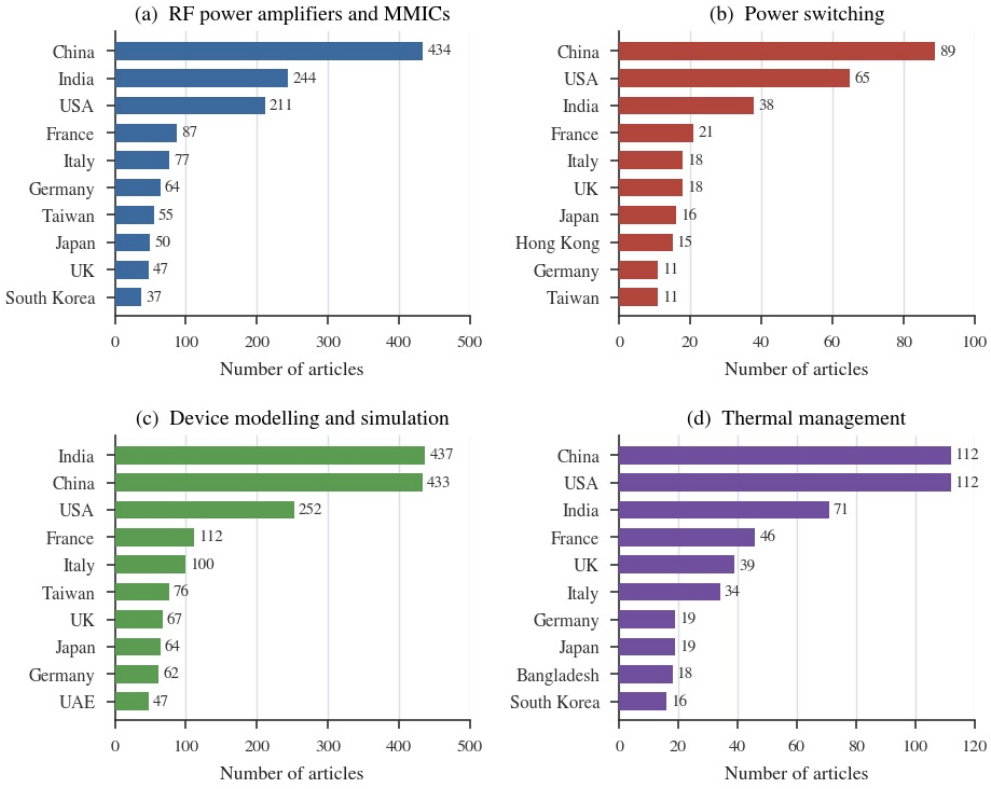

Fig. 7 Top 10 contributing countries for each of the four principal application categories: (a) RF Power Amplifiers and MMICs, (b) Power Switching, (c) Device Modelling and Simulation, and (d) Thermal Management.

Figure 7 disaggregates the top 10 contributing countries for each of the four application categories, revealing distinct geographical strengths and national research priorities.

RF Power Amplifiers and MMICs: As shown in Fig. 7(a), China has a commanding lead with 434 articles, followed by India (244) and the USA (211). France, Italy, and Germany follow with 87, 77, and 64 articles, respectively. This distribution aligns with the global trend of RF GaN development being concentrated in regions with strong telecommunications and defense industries.

Power Switching: The distribution for power electronic switching converters (Fig. 7(b)) is similarly dominated by China (89) and the USA (65), but India falls to third place with 38 articles. Notably, Hong Kong appears in the top 10 for this

specific application (15 articles), reflecting regional specialization in power electronics packaging and converter design.

Device Modeling and Simulation: A striking deviation from the overall publication trends is observed in device modeling and simulation (Fig. 7(c)). **India** takes the top spot with 437 articles, marginally edging out China (433), followed by the USA (252). This suggests that Indian research groups are heavily focused on the theoretical and simulation aspects of AlGaN/GaN HEMTs, possibly due to the lower capital costs associated with TCAD software compared to physical cleanroom fabrication. The UAE also makes its only top-10 appearance here with 47 articles, largely driven by the University of Sharjah (as noted in Section 3.3).

Thermal Management: For thermal management (Fig. 7(d)), China and the USA are tied at the top with 112 articles each, followed by India (71). France (46) and the UK (39) show strong contributions, likely driven by major aerospace and defense organizations that require robust thermal solutions for high-power RF systems. Bangladesh (18) and South Korea (16) round out the top 10, highlighting emerging research clusters in thermal characterization and packaging.

Overall, the country-level application distribution confirms that while China and the USA maintain broad dominance across all four categories, India's exceptional strength in device modeling/simulation and the specialized contributions of European nations in thermal management and RF design illustrate a highly diversified and globally collaborative research landscape.

3.9 Limitation of study

By restricting the search to wide-band-gap semiconductors within the title and abstract, the search results might not cover all AlGaN/GaN HEMT simulation-related studies available on Scopus. This is because some researchers did not refer to their systems as AlGaN/GaN HEMT, but instead used different terms (e.g., ultra-high semiconductors, power-controlled semiconductors). Furthermore, because the initial search query was restricted to articles mentioning "simulation," this study inherently captures only the simulation-focused segment of the literature. Therefore, the findings describe the internal evolution and trends within the simulation community itself, and do not aim to establish the relative centrality of simulation compared to experimental or fabrication-focused research in the wider AlGaN/GaN HEMT field. Additionally, while subject-area filters were applied, manual abstract screening was not performed for every record, meaning some peripheral papers may remain in the dataset. Also, co-occurrence analysis of author keywords covered only 76% of the 4,492 articles due to missing author keyword information from certain journals, namely, *RSC Advances*, *Scientific Reports*, *PLOS One*, and others.

Future studies to compare the outputs from multiple databases such as Scopus and Web of Science are recommended. The search results from Web of Science, for instance, display automatically the most popular articles in the field by a feature known as "hot paper," a feature that is still lacking in Scopus. This hot paper feature displays key papers that are recognized very soon after publication, reflected by a rapid and significant number of citations. Conducting bibliometric analysis using multiple data sources will be useful for a more comprehensive study.

4 Conclusion

This study has provided an overview of AlGaN/GaN HEMT simulation research trends based on 4,492 publications retrieved from the Scopus database. Publication growth has been rapid over the last 10 years, and it is anticipated to continue to rise. We have discovered countries and academic institutions (e.g., China, India, and the USA) that have a massive number of publications and strong international collaborations. These entities can serve as potential partners for researchers from countries with emerging programs in this field, offering opportunities to broaden international research collaborations. We have discussed several areas that are currently well-explored, such as materials science incorporating nanotechnology. We have also identified areas of recent concentrated activity within the simulation literature, such as quantum dots, heterostructures, and power transistors. While these are currently receiving significant attention, further technical reviews are required to assess their actual scientific promise, as high publication volume does not necessarily equate to long-term scientific impact. Machine learning, for example, is emerging as a promising direction specifically because it addresses the computational bottlenecks inherent in traditional TCAD simulations. Not to mention the continuous efforts to search for the next semiconductor generation for low energy, high efficiency, and high thermal capabilities.

Supplementary information. The authors declare that supplementary materials (Tables S2 and S3) accompany this manuscript.

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Declarations

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- **Competing interests:** The authors have no relevant financial or non-financial interests to disclose.
- **Ethics approval and consent to participate:** Not applicable. This study is a bibliometric analysis of publicly available academic literature and did not involve human participants or animals.
- **Consent for publication:** Not applicable.
- **Data availability:** The data that support the findings of this study are available from the Scopus database. The specific search query and screening criteria used to generate the dataset are fully described in the Methods section of this article. Derived data supporting the findings of this study are available from the corresponding authors upon reasonable request.
- **Materials availability:** Not applicable.
- **Code availability:** Not applicable.
- **Author contribution:** Ahmed Hussein conceived the study, designed the methodology, performed the data curation and formal analysis, created the visualizations, and wrote the original draft. Faizani Mohd Noor provided supervision, participated

in the conceptualization of the study, and reviewed and edited the manuscript. Both authors read and approved the final manuscript.

- **Use of AI tools:** The authors used generative AI tools (ChatGPT) solely for the purpose of AI-assisted copy editing, including improving the readability, grammar, and formatting of the human-generated text. The AI did not generate new scientific content, data, or conclusions. The authors take full responsibility for the accuracy, integrity, and final content of the manuscript, and both authors have reviewed and approved the final version.

Supplementary Materials

Supplementary Table S1: Search strategies and query strings used in Scopus

Search strategy and query strings used in the Scopus database.

Item	Theme	Search String
i	Central Theme	(ALL (algan gan) AND TITLE-ABS-KEY (hemt) AND ALL (simulation)) AND PUBYEAR > 1996 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "PHYS") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "MATH")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp"))

Supplementary Table S2: Top 30 journals publishing AlGaN/GaN HEMT simulation research

The top 30 journals publishing AlGaN/GaN HEMT simulation research.

Rank	Journal Name	Publications
1	IEEE Transactions on Electron Devices	354
2	Semiconductor Science and Technology	105
3	IEEE Electron Device Letters	84
4	Microelectronics Reliability	84
5	IEEE Transactions on Microwave Theory and Techniques	80
6	Micromachines	77
7	Solid State Electronics	74
8	Microelectronics Journal	67
9	Applied Physics Letters	62
10	IEEE Journal of the Electron Devices Society	59
11	International Journal of Numerical Modelling: Electronic Networks, Devices and Fields	59
12	Electronics (Switzerland)	56
13	Journal of Computational Electronics	52
14	Physica Status Solidi A: Applications and Materials Science	50
15	Superlattices and Microstructures	47
16	Micro and Nanostructures	46
17	Journal of Applied Physics	45
18	Journal of Electronic Materials	45
19	IEEE MTT-S International Microwave Symposium Digest	40
20	Journal of Semiconductors	40
21	IEEE Access	39
22	Chinese Physics B	37
23	IEEE International Reliability Physics Symposium Proceedings	36
24	IEEE Transactions on Power Electronics	34
25	IEEE Transactions on Nuclear Science	33
26	International Journal of RF and Microwave Computer-Aided Engineering	33
27	Physica Status Solidi C: Current Topics in Solid State Physics	33
28	Semiconductors	33
29	IEEE Transactions on Device and Materials Reliability	32
30	Silicon	32

Supplementary Table S3: The top 50 most productive institutions in AlGaN/GaN HEMT simulation research

The 50 most productive academic institutions in AlGaN/GaN HEMT simulation research.

Rank	Institution	Country	Publications
1	Xidian University	China	219
2	University of Electronic Science and Technology of China	China	166
3	Chinese Academy of Sciences	China	159
4	School of Microelectronics, Xidian University	China	157
5	Ministry of Education of the People's Republic of China	China	99
6	CNRS Centre National de la Recherche Scientifique	France	95
7	University of Delhi	India	94
8	Key Laboratory of Wide Band-Gap Semiconductor Materials and Devices, Ministry of Education, Xidian University	China	77
9	National Institute of Technology Silchar	India	70
10	XLIM Institut de Recherche	France	69
11	DRDO Solid State Physics Laboratory	India	68
12	University of Sharjah	UAE	64
13	Institut d'Electronique de Microélectronique et de Nanotechnologie (IEMN)	France	62
14	Karunya Institute of Technology and Sciences	India	62
15	Hangzhou Dianzi University	China	59
16	Institute of Microelectronics Chinese Academy of Sciences	China	58
17	University of Chinese Academy of Sciences	China	57
18	Université de Limoges	France	56
19	Nanjing Electronic Devices Institute	China	56
20	National Yang Ming Chiao Tung University	Taiwan	53
21	Università degli Studi di Messina	Italy	52
22	Université de Lille	France	52
23	Air Force Research Laboratory	USA	49
24	University of Bristol	UK	49
25	Nanjing University	China	48
26	Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik	Germany	48
27	Fraunhofer Institute for Applied Solid State Physics IAF	Germany	47
28	Deen Dayal Upadhyaya College	India	47
29	Università degli Studi di Padova	Italy	46
30	Peking University	China	46
31	Defence Research and Development Organisation India	India	46
32	Interuniversity Microelectronics Centre	Belgium	46
33	Indian Institute of Technology Kanpur	India	44
34	Hong Kong University of Science and Technology	Hong Kong	43
35	National Chiao Tung University	Taiwan	43
36	Tsinghua University	China	42
37	Arizona State University	USA	41
38	Università degli Studi di Modena e Reggio Emilia	Italy	41
39	University of Science and Technology of China	China	41
40	University of Florida	USA	39
41	University of California, Santa Barbara	USA	39
42	The Robert Mehrabian College of Engineering	USA	39
43	Zhejiang University	China	37
44	Beijing University of Technology	China	37
45	Macquarie University	Australia	36
46	Institute of Semiconductors Chinese Academy of Sciences	China	36
47	Suzhou Institute of Nano-tech and Nano-Bionics, Chinese Academy of Sciences	China	36
48	Herbert Wertheim College of Engineering	USA	36
49	University of Ferrara	Italy	35
50	SR University	India	35

Supplementary Table S4: Full list of 561 consolidated keywords

The 561 unique keywords retained after merging synonyms and congeneric phrases.

2deg, 2dhg, 3-d electrothermal simulation, 5g, access resistance, al2o3, algan, algan back barrier, algan barrier, algan hemt, algan/gan, algan/gan hemt,

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