

Review Article

Genetic Algorithms: Evolution, Current State, And Development Prospects

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Abstract

Over the past fifty years, genetic algorithms have progressed from theoretical applications to powerful engines in inferential optimization, machine learning, and cyber security systems. This paper presents an explanation of the improved performance of genetic algorithms based on bibliometric research of over 26,700 research papers indexed in Scopus, Web of Science, and IEEE Explore databases, covering a fifty-year period up to 2025. The study identifies key developmental stages, presents current research areas, and outlines the future of algorithms. It also highlights a shift in global leadership: during the last decade of the 20th century, the United States and the United Kingdom dominated, while in the last ten years, China has risen to prominence, accounting for over 40% of research output, with countries like India and Iran emerging as among the most productive. The research discusses the dynamics of 12 applied fields, with the highest growth rates officially recorded in 2020 in power systems, robotics, and artificial intelligence applications. This study reveals emerging trends, including the convergence of genetic algorithms with deep learning and machine learning, their integration with swarm intelligence, and their applications in sustainable energy and edge computing. It also highlights differentiable variables arising from quantum mechanics. These findings can provide a roadmap for researchers seeking to further develop and use genetic algorithms in considering rapid technological advancements.



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1. INTRODUCTION

The history of genetic algorithms began in 1975 when J. Holland established the basic principles for dealing with artificial systems [1]. Over the course of fifty years, this new scientific field has undergone significant development: from classical subplots to multi-objective and multi-content configurations integrated into engineering design, control tasks, biodata, and a number of other disciplines [2, 3]. By the beginning of the current century, new trends had emerged in: multi-objective optimization [4-6], constraint handling [4], and hybrid schemes incorporating simulated annealing and swarm algorithms [7, 8]. The benefits of extensive analysis of genetic algorithms stem from several factors. First, the rapid digital transformation and the emergence of new computational paradigms—such as edge computing, quantum accelerators, and unified learning—create entirely new opportunities for the application of genetic research. Second, to address global challenges, such as the transition to renewable energy and the reduction of carbon dioxide emissions, modern physical medicine requires optimization tools that can deliver results in a timely manner while adhering to specific standards.

Thirdly, a shift in the geographical landscape of research is occurring: while the USA and Great Britain dominated in the 1990s, in the 2020s, over 40% of publications originate from China, with India and Iran ranking among the top five most productive countries. Despite the abundance of publications, recent review works are limited either to specific applications or to the period before 2020. A systematic mapping of the fifty-year journey of GAs, encompassing the most recent data (including the full year 2025), has been absent until now. A need has arisen for a study that combines historical retrospective, analysis of the current state, and a forecast of the method's further development in the context of the latest technological trends. Of particular value is the identification of emerging trends — convergence with deep learning, the appearance of differentiable and quantum-inspired variants, and applications in edge and federated computing.

This present article fills this identified gap. The work is based on data from over 27,000 publications extracted from the three largest bibliographic platforms, enabling the identification of current trends with unprecedented completeness. Objective of the Study. present a systematized analysis of the development of genetic algorithms over the period 1975–2025, highlight key stages of evolution, determine current research directions, and characterize the prospects for further development of the method.



Research Tasks:

1. A selection of publications on genetic algorithms indexed in Scopus, Web of Science, and IEEE Explore databases over a fifty-year period up to 2025;
2. Study the dynamics of the publication process by year and research field, and select 12, types of genetic algorithm applications;
3. Examine the geographical diversity of research, identify shifts in leadership among nations, and assess the level of international collaboration;
4. Selecting the best trends for the period 2020-2025 based on an analysis of key keywords includes: convergence with deep learning, hybridization, bridging applications in energy and edge computing, and emerging new variants inspired by quantum computing;
5. Designing new directions for future research, including the development of standardized, adaptable, and ethically oriented models of genetic algorithms.

2. METHOD

The methodological basis of this research work relies on the principle of analytical methodological study, which allows for the quantitative evaluation of structural and evolutionary forms in the scientific field [9, 10]. Applying this approach to the field of genetic algorithms allows for the identification of key research areas, collaborative networks, thematic groups, and emerging fields.

2.1. Search Strategy:

The research paper was written across the domains of "Title-ABS-KEY" in Scopus, "Subject" in WoS, and "Detailed Data" in IEEE Explore. The period of the research papers covered the last fifty years. Document types included journal articles, conference proceedings, books, and book chapters.

2.2. Compilation of the Publication Corpus

The initial search yielded 241,058 records (Scopus – 156,943, WoS – 62,974, IEEE Xplore – 20,841). The data cleaning procedure involved several stages. Duplicate Removal. Duplicate records were identified using the Digital Object Identifier (DOI). For documents without a DOI (primarily older conference materials), fuzzy matching based on the combination of «title – first author – publication year» was applied. A total of 81,761 duplicates were removed. Title and Abstract Screening. The remaining 158,797 records were checked for thematic relevance. Publications where the term «genetic» refers to biological entities (genetic markers, gene expression, and hereditary diseases), as well as editorial materials, news items, and conference summaries, were excluded. At this stage, 93,943 records were removed. Full-Text Assessment. For 63,222 documents, full texts or extended abstracts were examined. Articles with vague formulations lacking a concrete contribution to the development or application of genetic algorithms, as well as publications with incomplete metadata, were excluded. Additionally, duplicate versions (e.g., preprint and published article) – 8,890 cases – and non-peer-reviewed materials – 6,994 records – were filtered out. Retracted articles and documents with insufficient metadata accounted for another 5,724 exclusions. The final corpus comprised 27,707 publications, deemed relevant and suitable for further analysis.

2.3. Classification by Subject Area

Classification was performed based on keywords and abstracts using a controlled vocabulary for each area. The main domains were as follows: Engineering Optimization (EO); Artificial Intelligence and Machine Learning (AIML); Energy Systems (ES); Robotics and Control Systems (RCS); Bioinformatics and Computational Biology (BCB); Finance and Economics (FE); Healthcare and Medical Applications (HMA); Transportation and Logistics (TL); Civil Infrastructure (CI); Environmental Science and Disaster Management (ESDM); Games and Entertainment (GE); and Physics and Chemistry (PC). An article containing keywords from multiple domains was assigned to the most appropriate category based on expert judgment.

2.4. Analysis and Visualization Tools

To construct co-authoring models, citation clusters, and keyword frequency profiles, VOSviewer version 1.6.20 was used [10]. Analysis settings included: a minimum keyword frequency of 2; a normalization method with correlation strength; a VOS clustering algorithm with a resolution of 1.0; and a minimum cluster size of 5. Statistical processing and visualization were performed using Python version 3.13 (libraries: pandas, matplotlib, seaborn). Sankey charts were used to illustrate the relationship between countries, institutions, and keywords. Heat maps were used to visualize the intensity of research activity over time. The mapping of country activity was performed using Python libraries (plotly, geopandas). To clarify the data, a logarithmic scale was applied to compensate for large variations in the absolute number of publications.

2.5. Methodological Limitations

Several limitations must be considered when discussing research findings. First, the language filter may have overlooked some recent works published in international journals in Japan, Germany, or China. However, these developments in key terminology have subsequently been reflected in international research, so the sampling bias is considered minor. Second, the indexing of older scientific conference proceedings in electronic databases is not always complete, leading to the undercounting of some outstanding works from the late 1970s and 1980s. Third, automated subject-field classification, supplemented by manual verification, does not completely eliminate subjectivity when selecting interdisciplinary research within a field. The procedures employed (standardized terminology and double-checking for ambiguities) have mitigated the impact of this factor.

3. RESULTS AND DISCUSSION

3.1. Overall Dynamics of Publication Activity

This analysis of 26,707 research papers reveals a significant and growing interest in genetic algorithms over the past fifty years. (Figure 1) illustrates the annual scientific publication patterns for the three fastest-growing fields: energy systems, robotics and control systems, and artificial intelligence and machine learning.

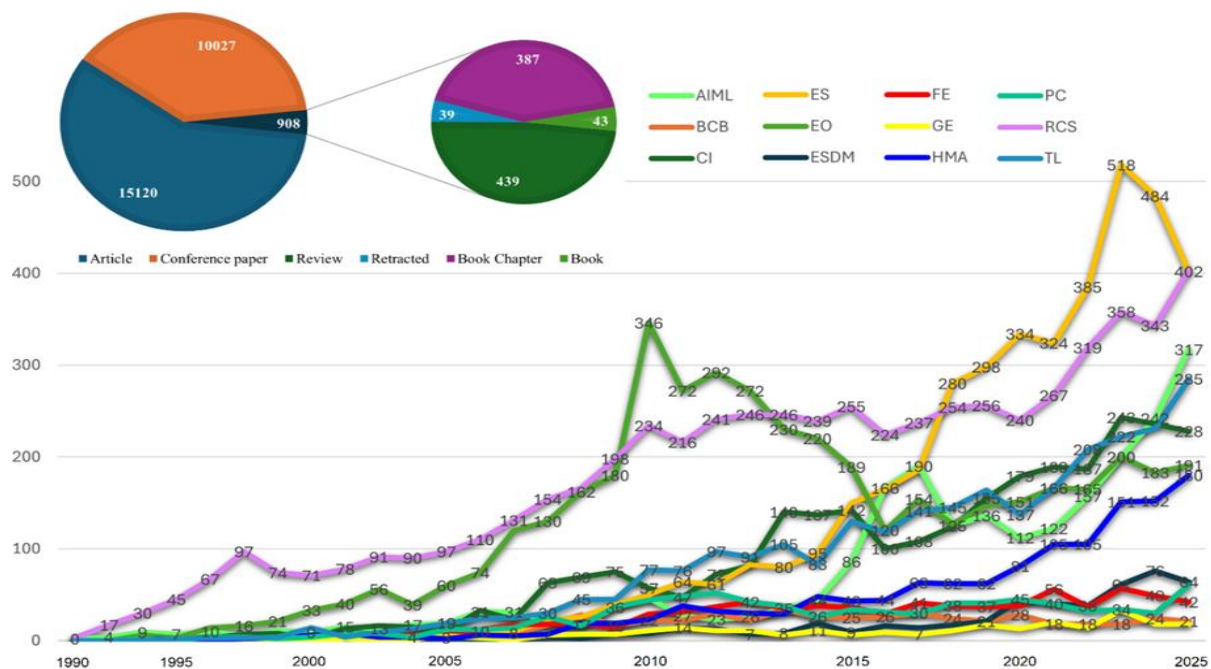


Figure (1). The mechanism of scientific research activity in three main thematic areas for the period from 1915 to 2025

The first surge occurred in the mid-1990s. The availability of computing power and fundamental research [2, 3] encouraged the widespread use of genetic algorithms in engineering work. A second surge (2001–2005) was associated with the development of highly efficient algorithms with a set of objectives, notably the NSGA-II algorithm [4, 5, 8]. The most significant growth has been observed since 2015, with annual article output increasing from 500 to 1,800 by 2024. The peak in 2022 (over 2,000 papers) coincided with a surge in research on intelligent networks and autonomous systems [14, 18]. The heat maps in (Figure 2) show the distribution of research across twelve subject areas over time. The highest density of work in the last five years has been observed in the fields of ES, RCS, and AIML, confirming a shift in research priorities compared to the 1990s and 2000s when optimization engineering (EO) was prevalent.

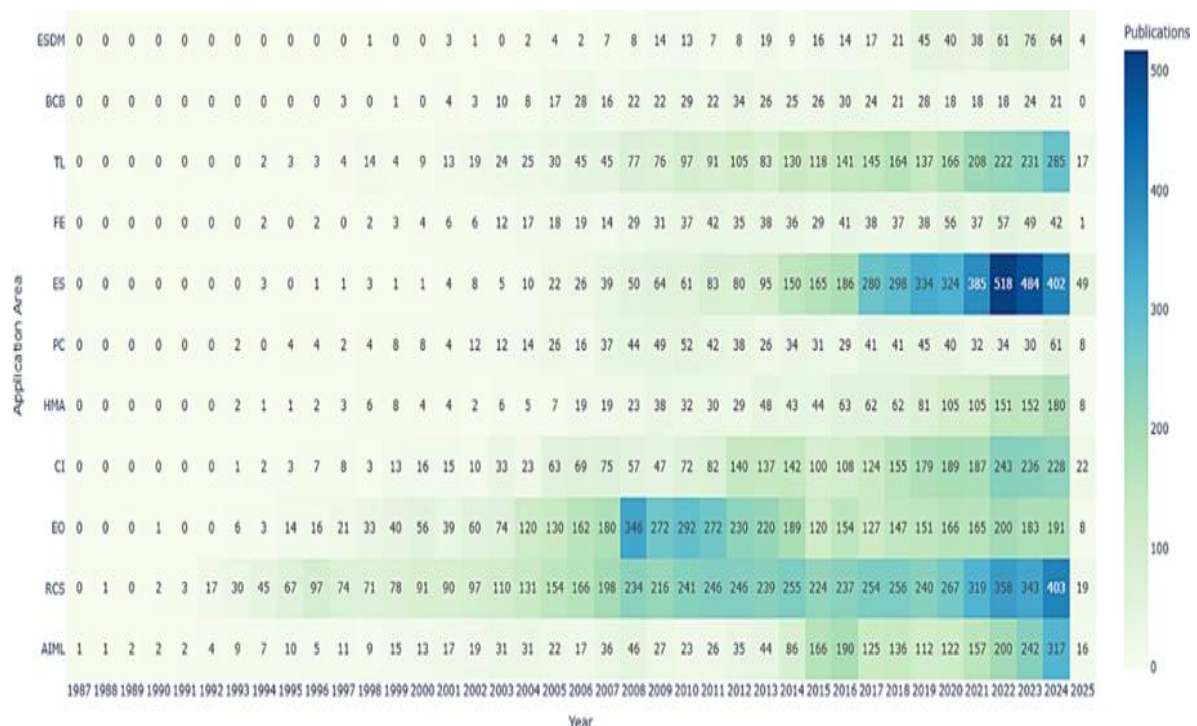


Figure (2). Heat maps showing the breakdown of scientific research across subject areas for fifty years (1975-2025)

3.2. Geographical Distribution of Research

The international map showing the geographical distribution of research papers in the field of genetic algorithms (Figure 3) reveals a significant shift in the geographical structure of research. While the United States and Great Britain accounted for nearly 60% of scientific research in the 1990s, by 2005 China's share had equaled that of the United States. During the period 2021–2025, China maintained its leading position (42% of total publications), followed by India (17%) and Iran (6%). The United States, meanwhile, slipped to fourth place (approximately 7%).

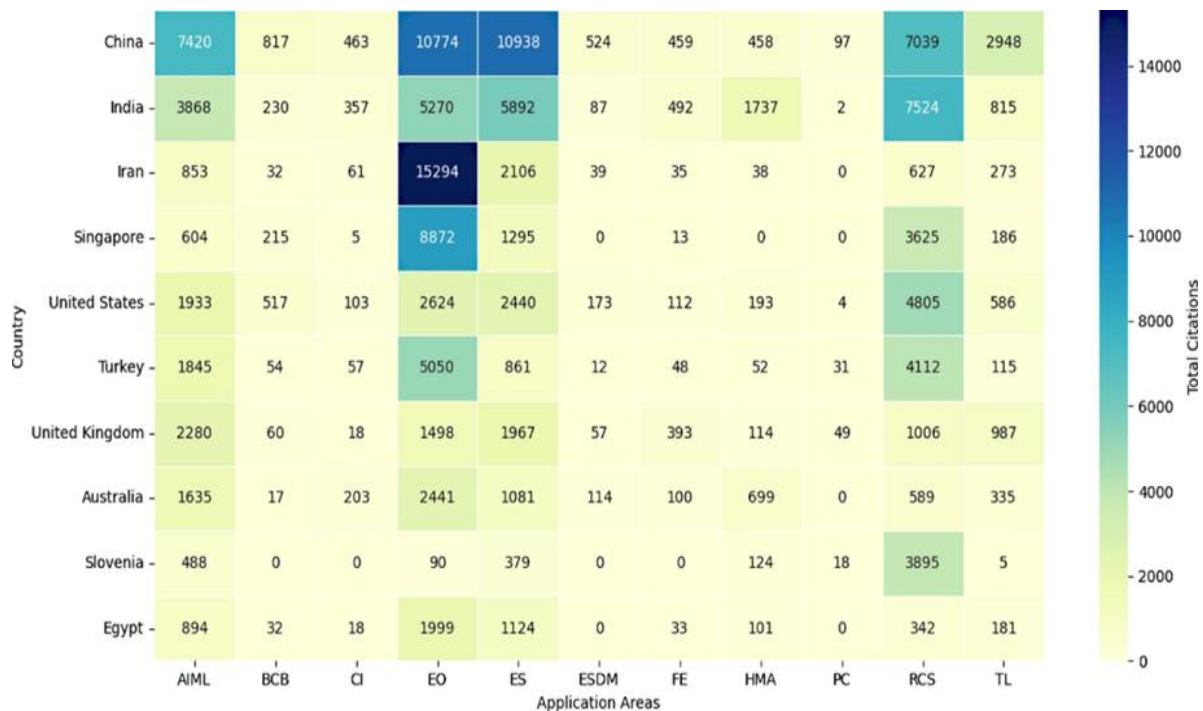


Figure (3). Distribution of international scientific research activity in the field of genetic algorithms (logarithmic scale).

This shift is evident in the increased funding allocated to modern digital transformation and clean energy in Asia and the widespread integration of associate engineers into vocational (engineering and industrial) education in India and Iran [14, 17, 18]. The share of international research partnerships increased from 14% in 1995–2000 to 28% in 2021–2025, demonstrating the strengthening of international collaboration. Transcontinental links remain dominant (82%), creating opportunities for expanding transatlantic and regional partnerships.

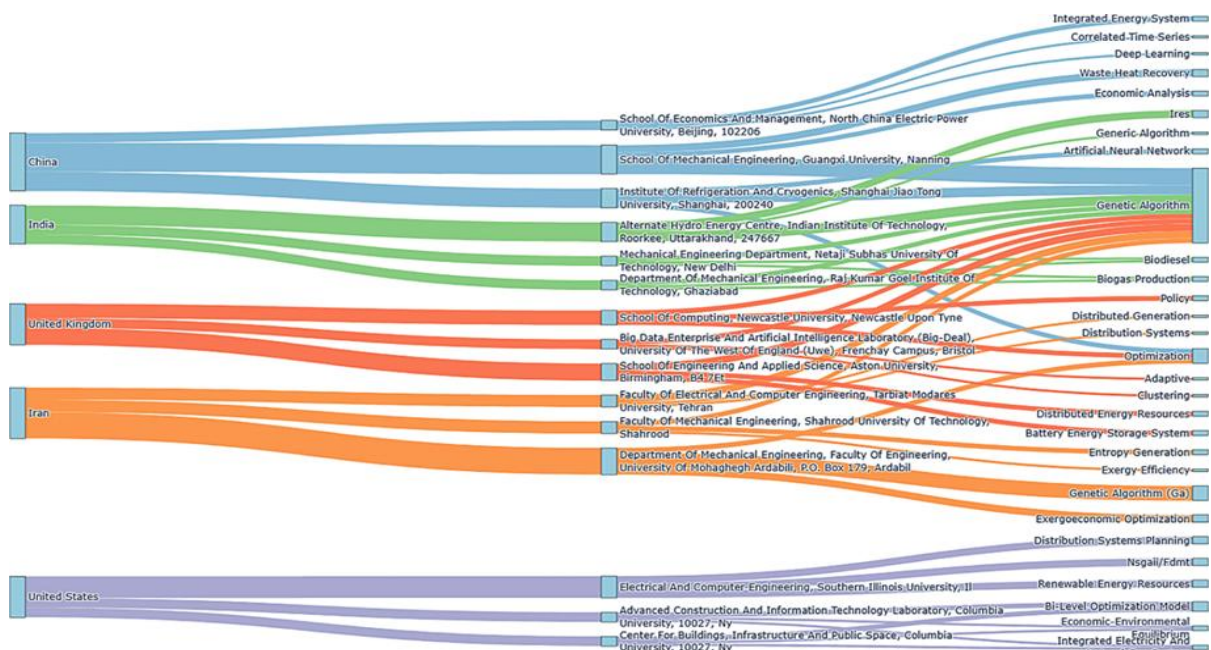


Figure (4). Sankey diagram for the new energy systems

3.3. Analysis of Key Subject Areas

Of these 12 fields, robotics and control systems (approximately 6,100 articles) and engineering quality improvement (approximately 4,400 articles) continue to lead in terms of the absolute number of publications. The following fields are projected to experience the highest growth rates during the period 2020–2025: a) diversified energy systems (28% year-on-year increase); b) artificial intelligence and machine learning (22% increase); and c) healthcare and medical applications (19% increase). In the field of energy systems management, significant and fundamental efforts are being made toward the optimal allocation, management, and storage of renewable energy sources and smart microgrids [14, 18]. Genetic algorithms are being used to balance technical, economic, and environmental indicators, including CO₂ emissions reduction and equipment lifecycle considerations. (Figure 4) shows the Sankey diagram, which illustrates the correlations between countries, institutions, and keywords in the field of energy systems.

In the field of AI-enhanced machine learning, genetic algorithms are used as super-optimizers for deep neural networks [11-13]. They contribute to solving tasks such as neural network structure search (NAS), hyperparameter tuning, and feature selection using genetic algorithms within hybrid automated machine learning pathways. Differentiable variables have been directly incorporated into PyTorch/TensorFlow computational graphs. Remote control robots (RCS) extensively use genetic algorithms for motion planning in dynamic environments, coordinating drone swarms, and the co-evolution of exoskeletons and controllers [10, 15]. In the field of human motion analysis (HMA), a growing number of studies highlight the selection of diagnostic features from multidimensional medical data (EEG, ECG, and genetic profiles) [16, 20].

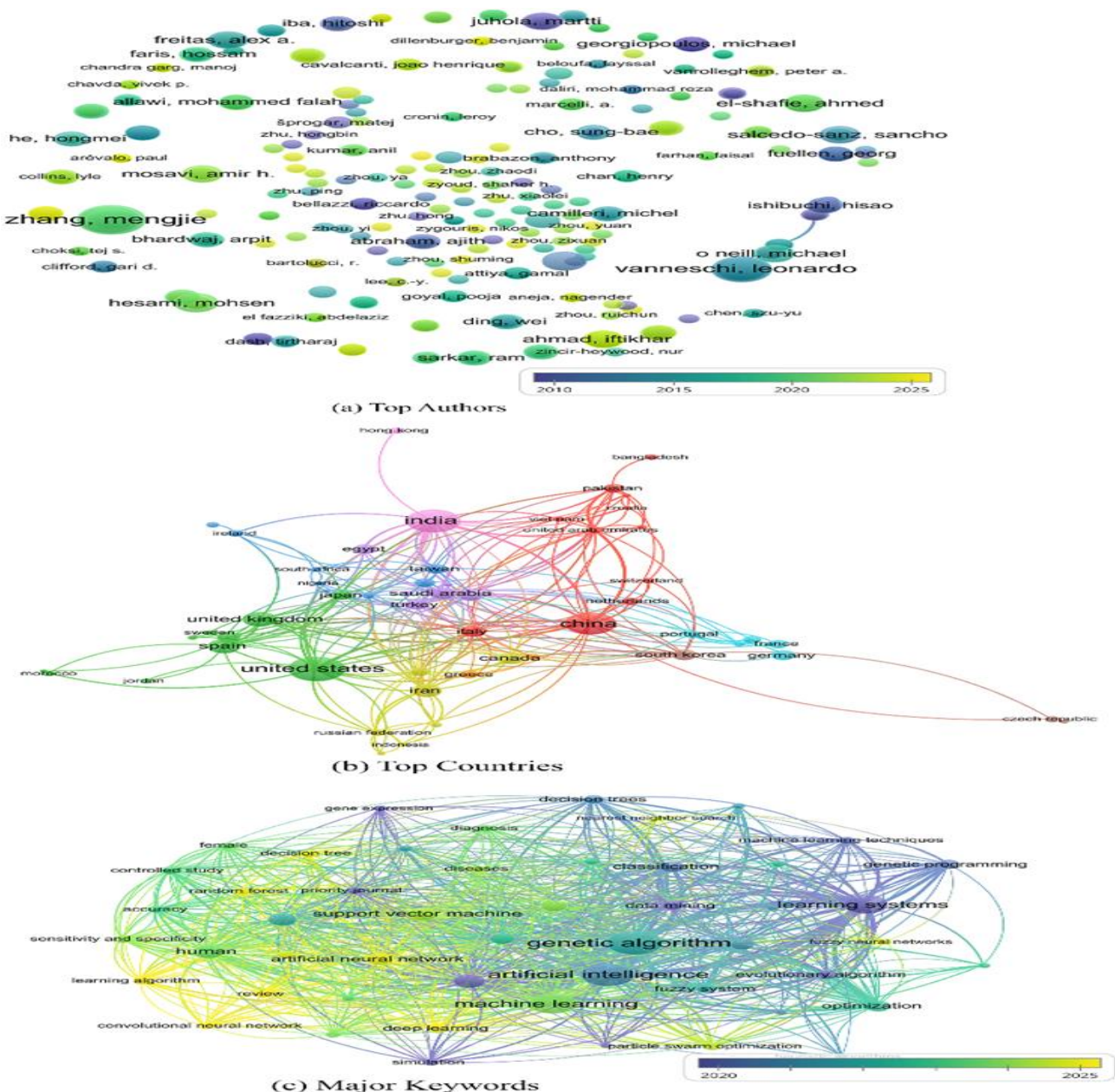


Figure (5). Fragment of the co-authorship network in the AI and machine learning domain

3.4. Contemporary Trends

An audit of the semantic core of keywords from 2020–2025 identified five main directions:

- Convergence with Deep Learning and AutoML – GAs optimize neural network architectures and hyperparameters; the share of such works in AIML exceeded 40% in 2024 [11–13, 20].
- Hybridization with Other Metaheuristics – Over 30% of articles from 2023–2025 combine GAs with swarm algorithms, differential evolution, or local search [11, 15].
- Sustainable Energy – in ES, GAs incorporate environmental constraints, including CO₂ emissions and equipment life cycles [14, 18].
- Edge and Federated Computing – The development of Edge AI demands lightweight GA variants for mobile devices and microcontrollers [17, 20].

Quantum and Differentiable GAs – currently accounting for about 3% and this share doubles every two years. Quantum-inspired operators and differentiable schemes open new possibilities for combinatorial optimization [19, 20].

3.5. Analysis of Key Subject Areas

Network Structure of the Research Community. Analysis of co-authorship networks revealed the formation of dense national clusters with strengthening international links. (Figure 5) shows a fragment of the co-author network in the AIML domain, illustrating the interaction between research groups from China, India, and Iran. The most influential authors whose work forms the basis of contemporary research include D. Goldberg, K. Deb, and J. Holland [2, 4–6]. In the last five years, leadership in publication count has shifted to Asian scientists, correlating with the overall geographical shift. The co-presence network of keywords shows a high pattern of subject clusters. It clearly shows clusters that correspond to classical applications (optimization, control) and new trends (deep learning, edge computing, quantum algorithms).

4. CONCLUSION:

The main findings of this work can be summarized as follows: The international research landscape has undergone a complete shift in geographical leadership. While the United States and Great Britain led in the 1990s, over 40% of articles published in 2021–2025 originated from the People's Republic of China, with India and Iran ranking among the top five most productive countries (Figure 3). This shift reflects increased funding for digital transformation and clean energy in Asia [14, 17, 18]. The proportion of international co-authored works rose to 28%, indicating growing international collaboration.

4.1. Subject Area Structure

Increased activity in energy systems, artificial intelligence, and healthcare will drive the highest growth rates in scientific research publications during the period 2020–2025. The heat map in (Figure 2) clearly illustrates the shift in priorities compared to the 1990s–2000s, when engineering optimization was the dominant field. In energy systems, genetic algorithms address the challenges of optimizing renewable energy sources, managing storage, and reducing carbon dioxide emissions [14, 18]. In artificial intelligence, genetic algorithms are used as super-optimizers for deep neural networks, enabling structure search and hyperparameter tuning [11–13].

4.2. Methodological Evolution

The development of GAs has progressed from canonical binary schemes [1, 2] to hybrid constructs combining genetic operators with swarm algorithms, differential evolution, and local search [11, 15]. Multi-objective algorithms of the NSGA family have become a standard in engineering design [4–6, 8]. The Sankey diagram captured contemporary research chains in the energy domain, linking countries, institutions, and keywords.

4.3. Latest Trends

The following key trends were identified:

1. Convergence with deep learning and automated machine learning, where genetic algorithms act as catalysts for improving neural network architectures and their high coefficients;
2. Hybridization with other inferential models, currently encompassing over 30% of articles;
3. Application in sustainable energy and carbon emission reduction tasks;
4. Peripheral and unified computing, requiring lightweight and energy-efficient genetic algorithms;
5. Discovery of novel differentiable genetic algorithms inspired by quantum mechanics, opening new venues for combinatorial optimization;
6. The co-authoring network has fostered the formation of strong national clusters while strengthening international ties, particularly in artificial intelligence and machine learning.

4.4. Limitations and Validity

When discussing the research paper's findings, consideration was given to the factors related to language filtering, the completeness of the indexing of older materials, and subjectivity in domain classification. The measures taken (standardized vocabulary and double-checking) mitigated the impact of these factors. Independent, multi-directional indicators confirm the main trends and can be considered a comprehensive indicator.

4.5. Prospects for Further Research

The identified future development directions are as follows:

- Creating a unified, edge-to-edge model of genetic algorithms while maintaining data privacy;
- Developing differentiable, quantum-mechanical-inspired models to address large-scale problems;
- Integrating sustainability and ethical considerations into objective functions;
- Standardizing problem criteria and benchmarks to ensure reproducibility of results;
- Integrating with analyzable artificial intelligence in regulated fields (medicine, finance).

These directions collectively confirm that genetic algorithms remain a dynamic and scalable field, ready to meet the challenges of future decades.

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