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Research Article

Bat Optimization Algorithm Research Output from 2010 to 2025 through Bradford's Law

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ABSTRACT

The present paper aims to evaluate the growth of research output on the Bat Optimization Algorithm (BOA) during the period 2010-2025 using a scientometric approach. The purpose of this study is to evaluate the research status of the Bat Optimization Algorithm (BOA) and to help evaluate the academic development and new research trends and promote faster collaboration. Sources were accessed on 4 February 2026 from Web of Science Core Collection. The growth rate, sources, and citation counts were evaluated thoroughly. The research output of the BOA from 2010-2025 clearly shows the evolution of the BOA from a nascent idea to a well-established and widely used metaheuristic approach. The publication trend shows a slow start with a sudden increase after 2015 and a peak in 2022-2023. The sources were analyzed using Bradford's Law, which shows a strong core-periphery effect. The BOA research output has clearly moved from a purely theoretical approach to a multitude of applications with a steady growth rate, international cooperation, and diversification. The study provides a comprehensive bibliometric assessment of BOA research output using productivity, citation, collaboration, and Bradford distribution indicators.

Keywords: Bat Optimization Algorithm, Bibliometric Analysis, Bradford's Law of Scattering, Metaheuristic Optimization, Research Productivity, Scientometric Mapping.

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INTRODUCTION

The Bat Optimization Algorithm (BOA) was first introduced by Yang, (2010) in the paper "A New Metaheuristic Bat-Inspired Algorithm" presented at the Nature-Inspired Cooperative Strategies for Optimization (NICSO 2010) international conference, which was later published by Springer in the series "Studies in Computational Intelligence." BOA was inspired by the echolocation behaviour of microbats, which use ultrasonic sound waves for prey detection and navigation (Yang, 2010) formulated the echolocation characteristics of bats, including frequency tuning, loudness variation, and pulse emission rate, into a series of mathematical formulations for the search process of the BOA algorithm. BOA integrates the fundamental concepts of Particle Swarm Optimisation (PSO) with adaptive control techniques for the search process parameters, thus achieving a balance between exploration and exploitation in the search space. The author validated BA with benchmark optimization functions, demonstrating the effectiveness of the BOA algorithm. Between 2011 and 2013, the BOA algorithm became widely recognized and was effectively utilized in engineering design, structural optimization, and power system optimization issues. Enhanced and merged versions of the BOA algorithm were suggested for superior performance. Since 2014, BOA variants like the Binary Bat Algorithm, Chaotic Bat Algorithm, and Multi-objective Bat Algorithm have been introduced to tackle binary and multi-objective optimization issues, respectively. Lately, the BOA algorithm has become widely used for addressing various real-world optimization issues, such as those in machine learning, image processing, wireless sensor networks, and medical diagnostics, among others. Consequently, the Bat Optimisation Algorithm has demonstrated a notable impact on the area of swarm intelligence optimization methods.

REVIEW OF LITERATURE

The Bat Algorithm's adaptability has led to its widespread adoption in different areas. In geophysics, the Bat Algorithm has been studied for its ability to solve gravity data inversion as well as accurately interpret magnetic data problems. They were solved without any prior knowledge or constraints imposed from the model (Essa and Diab, 2022; Essa and Diab, 2023)This property for multimodal optimisation of geophysical problems makes

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the Bat Algorithm preferable for solving such complex issues. Generally these problems represent a high challenge with respect to regular gradient-based optimisation algorithms (Essa and Diab, 2022). In other fields such as industrial studies, the Bat Algorithm has worked for solving complex problems like truss structure optimisation, manufacturing process optimisation, supply chain management, etc. These studies proved the use of the Bat Algorithm in NP-hard optimisation. Its adaptability also includes its application in emerging technologies such as network-on-chip routing frameworks for energy-efficient computing and workflow scheduling in cloud computing environments to reduce energy consumption (Dao and Nguyen, 2025). Recent developments have made the Bat Optimisation Algorithm even more effective in dealing with various problems in the biomedical and data science fields. For instance, the Bat Optimisation Algorithm was used in feature selection in software fault detection, where relevant and discriminative features are selected from a large number of software metrics to build accurate prediction models (Umar *et al.*, 2024). In medicine, BOA was used in gene selection from large-scale medical data to find disease-related genes and in EEG channel selection for the rehabilitation of stroke patients using brain-computer interfaces (Agarwal and Kumar, 2022). These recent developments have shown the effectiveness of BOA in dealing with problems with huge and intricate relationships and in situations where computations are expensive.

As it has been discussed in the literature, since 2010, the Bat Algorithm (BA) and its variants have evolved from a simple swarm intelligence to specific, hybrid and application-based metaheuristics. BA is known as a powerful nature-inspired optimizer in early publications, and the recent works are focusing on overcoming its inherent drawbacks, such as, trapping in local optima, premature convergence and sensitivity to parameters. In 2025, some studies suggest that improved or hybrid BAs will be able to better balance exploration and exploitation. The chaos improved, and Lévy flight-based BA variants address the problem of local optima trapping and insufficient local search, and they outperform classical BA and other metaheuristics on the benchmark functions (Younus *et al.*, 2025). Group-based and cross-group-based frameworks modify attraction and movement behaviours to sustain population diversity and prevent premature convergence. They have shown promising results when combined with BA and other swarm techniques, particularly in feature selection. (Robson *et al.*, 2026). In power and energy systems, improved BA is used for optimal scheduling of wind-PV-pumped storage systems, integrating chaotic mapping, adaptive step size, and Cauchy perturbations to boost convergence and global search, increasing system revenue versus standard BA and PSO (Fan *et al.*, 2025), while modified BA with adaptive parameters and elitist learning improves economic dispatch performance compared with GA, PSO, and the original BA. In hydrothermal economic dispatch with valve-point effects, BA achieves somewhat lower operating costs than Artificial Bee Colony but at the expense of longer iterations, indicating a cost-speed trade-off (Hernández *et al.*, 2025). BA has been used in control and robotics to optimize hybrid neural-FOPID controllers for robot manipulators to improve tracking robustness under disturbances (Oleiwi *et al.*, 2025). Additionally, a leader-based BA that exploits robot orientation for swarm guidance improves path accuracy and convergence in mobile robot localization compared to newer metaheuristics (Araujo-Neto *et al.*, 2025). BA is being used in a variety of ways, including combining it with genetic algorithms for smart building energy management, integrating it with genetic algorithms in hybrid biclustering for gene expression data, and using it as a hyperparameter tuner in machine learning pipelines for nanoparticle characterization (Aghanasab *et al.*, 2025; Wu *et al.*, 2025). In electrical systems, a BA variation with a "balloon effect" dynamically modifies parameters in real time, boosting robustness in DC motor and load-frequency control tasks (Tarek *et al.*, 2026). Broader surveys and comparative studies place BA in a family of metaheuristics in which no single algorithm dominates: BA and Grey Wolf Optimizer excel at continuous engineering design, while other algorithms excel at discrete or combinatorial problems, and current challenges include parameter tuning, convergence speed, and robustness against local optima *(Ahmed et al.*, 2025; Ahmed and Ibrahim, 2025). The secondary-data reviews for supply chain management point to the potential of BA for multi-objective inventory, routing and demand forecasting. The usual results are lower costs and improved resource allocation. They also recommend more systematic bibliometric mapping of BA applications, focusing on the gaps (Geevarghese *et al.*, 2025). The Bat Algorithm (BA) is an established and matured meta-heuristic still under development, used in hybrid, custom-made frameworks and complicated real-world systems to solve multi-objective, limited and dynamic optimization problems.

METHODOLOGY

The research is based on a quantitative bibliometric approach to analyze the academic production of the selected research area in the period of 2010-2025. Bibliographic data were extracted from the Web of Science Core Collection database. A more comprehensive and robust dataset was derived using a wider range of keywords and alternative expressions. The search terms were "Bat optimization algorithm," "Bat algorithm," "enhanced Bat algorithm," "Binary Bat algorithm," "Bat optimization," "hybrid Bat algorithm," "chaotic Bat algorithm," and "metaheuristic Bat algorithm. To preserve the consistency of the dataset, the study period was limited to 31 December 2025, and no incomplete or partial records in the year 2026 were included. The final dataset, after cleaning and removal of inconsistencies, consisted of 1,018 documents from 400 sources. The methodology for this research is based on established scoring metrics and frequency ranking algorithms. These simple methods have been chosen in general because they give a clear, direct and unadulterated mathematical

picture of productivity and are best suited to show the basic structural characteristics of this particular field. Further studies of this distribution were carried out by using Bradford's law of scattering. The purpose of this law is to observe whether the research of Bat Optimization Algorithm (BOA) follows the general distribution trend of information, and to find the main "core journals" influencing the discipline. The data set is very concentrated with 1,018 documents, but large enough for a meaningful Bradford analysis. Empirical bibliometric studies show that new specialized algorithmic fields (post 2010) tend to concentrate their important output in a few leading journals. Bradford's Law allows us to mathematically isolate this very productive 'core zone' (Zone 1) from the rest of the literature and to provide clear and actionable advice for researchers and institutions that wish to identify the most influential publication outlets in the field. The study offers a strong theoretical foundation to comprehend the structural topology of the area of Bat Optimization Algorithm (BOA) based on classical and modern literature on information distribution. The distribution of literature in publishing outlets is analyzed using Bradford's Law of Scattering, which is further improved by Brookes' mathematical model, (Brookes, 1977) given by

$$R(x) = a + b \log (x)$$

R(x) is the total number of papers in the top x journals. a and b are constants of the Bradford distribution Egghe (1990) presented sophisticated bibliometric formulations, which we use to check our dataset for completeness and structural accuracy. Egghe combines mathematically Bradford's Law and Leimkuhler's model. These models provide algebraic tools for modeling cumulative distribution and bibliographic completeness of a specialized field. The dataset of 1,018 documents is found to be adequate for investigating publication scattering patterns and core sources of BOA research following the theoretical framework suggested by Egghe (1990). The practical validity of using Bradford and Leimkuhler distributions to map rapidly changing computational and algorithmic frameworks has been well established in recent scientometric literature (Gupta and Singh, 2023) found that the Leimkuhler model provides very accurate quantitative estimates of research trajectories in specialized subfields of computer science and engineering. In addition, (Gupta *et al.*, 2024) used Bradford productivity distributions and sophisticated network path analysis to identify thematic evolution and growth trends in rapidly developing, highly technical computational fields. It is very appropriate to apply the distribution of Bradford to the literature of the BOA following modern examples. This enables the present study to extend beyond mere frequency counts and to chart the real thematic and structural core of the field. Finally, literature scattering, empirically demonstrated by Sudhier (2010), in highly specialized technical domains, generally involves a marked divide between a highly concentrated core of primary journals and a wide, distributed periphery of multidisciplinary venues. With this multi-zoned approach, this work can filter the peripheral citation noise and systematically identify the main channels of knowledge dissemination. This provides researchers and institutions with a clear roadmap of the most influential publication venues in metaheuristic optimization. Data extracted included author names, year of publication, source titles, author keywords, abstracts, citations, references and collaboration data. The productivity and impact of the research were assessed through the use of descriptive indices and various bibliometrics. The indicators were annual growth rate (10.53%), total number of authors (3,392), number of single-authored documents (40), average number of citations per document (25.38), total references (8,868), average document age (4.87 years). Collaboration practices were quantified through co-authorship data (authors per document: 4.2, rate of international co-authorship: 35.17%). The research used keyword analysis (3,184 author keywords) to identify major themes, emerging trends and thematic evolution in the domain. Citation analysis identified key publications and academic foundations of the discipline. Collaboration networks, keyword occurrence patterns and thematic clusters that conceptually and socially express the domain were mapped using network visualization techniques (Eck and Waltman, 2010). The data were cleaned (removing duplicates and inconsistencies) and analyzed. Such a methodology framework enables a structured, transparent and reproducible assessment of research quality, collaboration dynamics and thematic evolution within a specific scientific field.

LIMITATIONS

The present study contains the complete survey on the field of Bat Optimization Algorithm (BOA), but some limitations are to be pointed out.

The study is restricted to publications in the Web of Science Core Collection database. We excluded publications indexed only in Scopus, Dimensions, Google Scholar or other databases. The dataset contains 1,018 documents and is enough to characterize the BOA research domain. In future work, multiple databases may be combined to increase coverage.

BOA is a specific research area created in 2010, so the records obtained represent a big percentage of the literature indexed in Web of Science Core Collection. Also, bibliometric measures are largely based on publishing and citation trends and may not be able to capture the qualitative impact of research outputs.

BOA is a well-defined metaheuristic domain developed in 2010, and as such, it has a more concentrated body of literature than broader areas such as computer science in general. The dataset is a good representation of the dense 'core zone' of literature according to Bradford's Law (347 publications from the top 12 primary journals) and has sufficient statistical rigour to be able to illustrate well global collaboration and thematic shifts.

Figure 1 shows that a time-based assessment of publications demonstrates a significant increase in research output from 2010-2025. The publication activity was relatively low in the first years starting at 0.10% in 2010 and slowly increasing to 6.25% in 2018. A remarkable surge in research output was noted from 2019 onwards, with publication proportions rising from 8.94% in 2019 to 9.43% in 2020, then substantially increasing to 13.65% in 2021 and further climbing to 14.44% in 2022.

There was a small decline later, but the publication output still remained at a high level, with 12.18%, 11.20%, and 12.28% in 2023, 2024, and 2025, respectively. The citation trend shows that the earlier publications have higher citation shares and the recent ones have lower shares. This is expected as older studies have had more time to accumulate citations. The number of publications in the last years is a sign of an increasing academic interest and fast developments in this research area, with over fifty percent of the total output being produced after 2019. The trend shows the development of a well-established and fast-growing research area with ongoing expansion and an increasing number of scholarly contributions.

DATA ANALYSIS AND DISCUSSION

The content sources were mainly related to the investigation of a specific field of work, determined by the number of written documents, as illustrated in Figure 2. Among the journals, EEE Access ranks first in terms of the publication volume with the highest number of articles (99 documents), which shows its vital position in the dissemination of information in this field. IEEE Access focuses on publishing works in engineering, computer science, and applied technologies. This shows a significant focus on technology and engineering in the domain. The second most prolific source is Scientific Reports, with 40 publications, followed by Applied Sciences- Basel, with 37 articles. These journals are interdisciplinary and represent the whole research field. Other important contributors are energy, Mathematics, Electronics, Sustainability, and Sensors, each with a moderate number of articles. Practical and solution-oriented dimensions of the discipline are covered in journals on energy, computational methods, electronics, and sustainability, among others. Moreover, journals such as Computational Intelligence and Neuroscience and CMC-Computers, Materials and Continua are indicative of the integration of elements of artificial intelligence, computational modeling, and materials science. The distribution of publications across these resources indicates a highly accessible, interdisciplinary research area and a strong context of engineering, computational science, and sustainability-oriented inquiries. Visible in the technological structure as well as the impressive publication efforts of the IEEE Method is its power.

Figure 3 shows the distribution of journals according to Bradford's Law by examining the sources that are active in the key activities where this research produces the most publications. This graph shows that from the most productive journal to other journals in the sequence, there are very few articles published under a particular heading type. IEEE Access is the journal with the largest number of articles published at the beginning of the distribution. Scientific Reports is the second journal with the number of articles. The publications in these areas form the "core zone" illustrated by the shaded area. This core area is the source of many publications based on Bradford's Law, and it has only a few very productive sources. At the next level the number of articles per source falls markedly along the rank axis. The second and third zones also have additional journals, each one producing fewer publications than the previous. This is consistent with the bibliometric principle of Bradford that literature in a given field is concentrated in a few journals, rather than scattered widely.

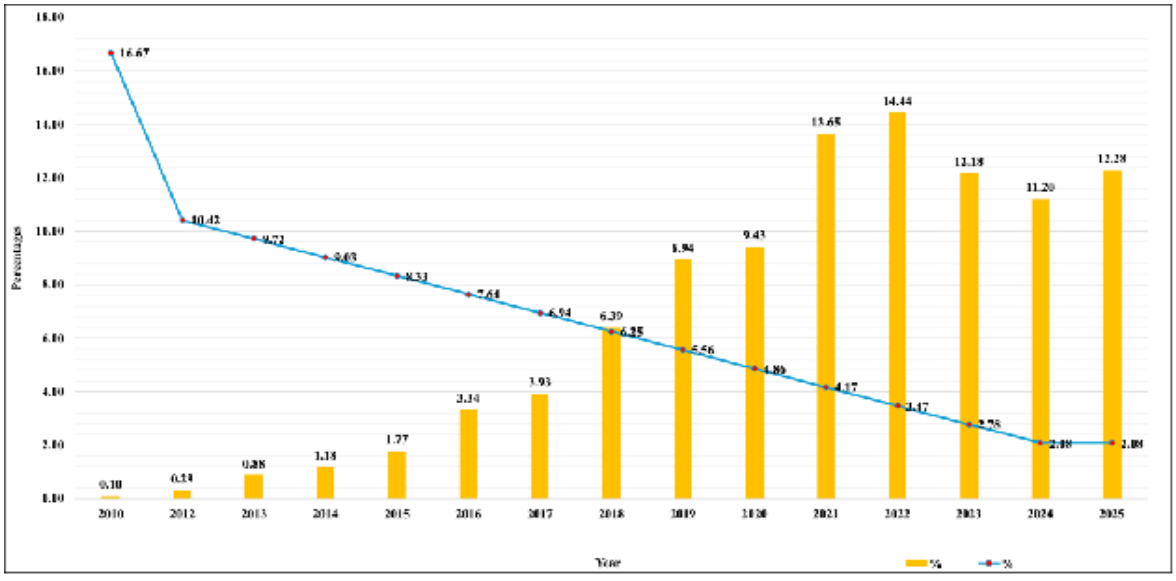

Figure 1: Annual Publication and Citation Trends in Bat Optimization Algorithm Research (2010-2025) Note: Bars represent the percentage share of annual publications, while the line indicates the percentage share of annual citations.

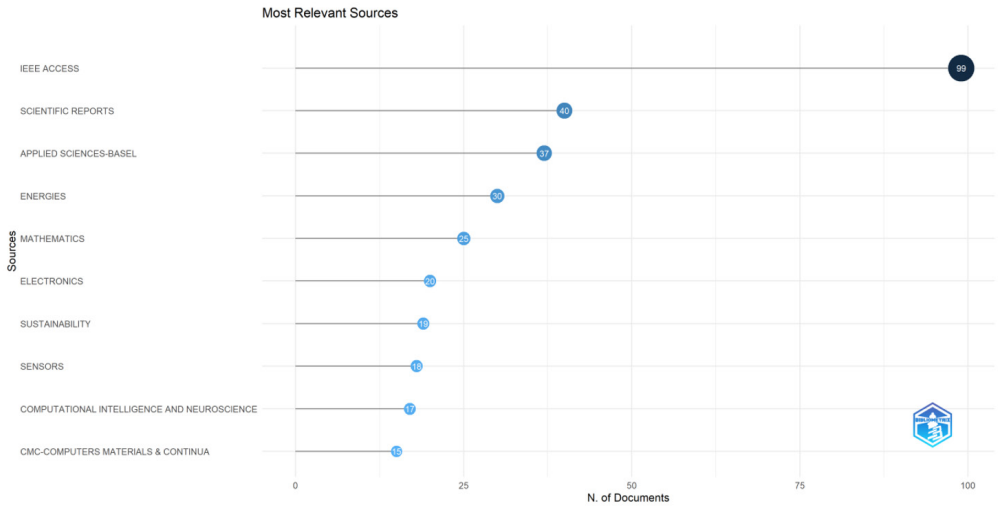

Figure 2: Most Relevant sources in Bat Optimisation Algorithms Research.

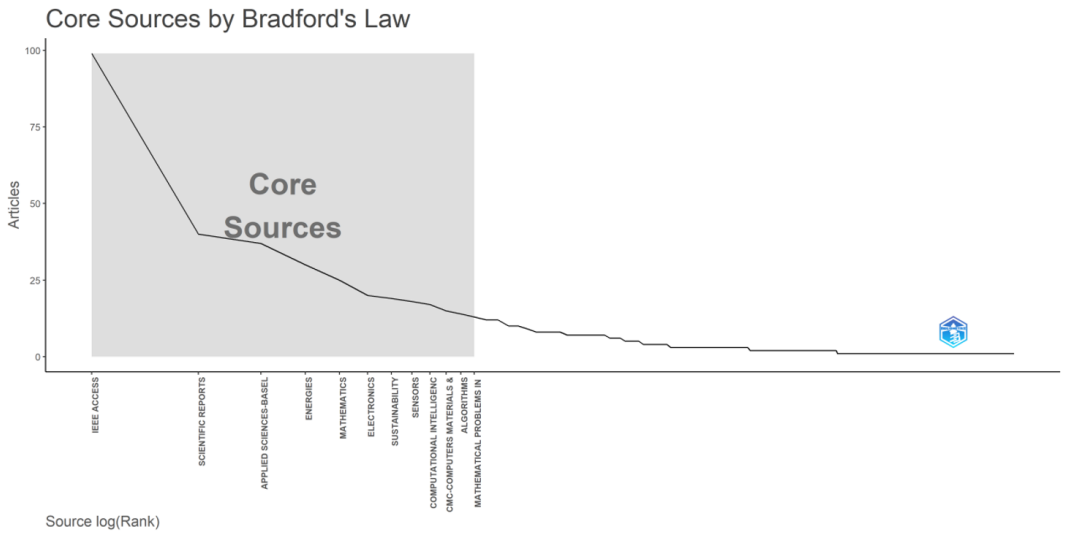

Figure 3: Bradford's law in Bat Optimisation Algorithms Research.

However, the number of contributing sources is sizeable, and this is a testimony of the interdisciplinary character of the field, and it helps in the diffusion of research results in diverse engineering, sustainability, computational intelligence, and materials science publications. The data are driven by a solid core-periphery model, which highlights that a small number of leading journals also contribute a lot to the creation and spread of knowledge in the discipline. The 1,018 documents from 400 sources are distributed in three Bradford zones. An important aspect is that classical Bradford's Law should be visible in the analysis, mainly because the most prolific sources are the highest-ranking journals, followed by a wider distribution from the less prolific sources.

Zone 1 (Core Sources): 12 journals; 347 articles. This core group is mainly represented by IEEE Access (99 articles), Scientific Reports (40) and Applied Sciences-Basel (37). These journals are the most important and favored venues by the community. The small size of the collection is an obvious sign of the centralization of the distribution of this research and reflects the focus of the article on this region.

In Zone 2, ranks ~13-96, there are many more journals that were published with moderate regularity. Individually they publish fewer (typically between 2 and 12 articles), but collectively they account for a large part of the total output. This area shows the growing and interdisciplinary nature of the field spreading in different directions including engineering, artificial intelligence, energy and applied sciences publications.

Zone 3 has the largest number of sources (over 300) and most of the journals publish only one publication. The long-tail distribution means that this study does not cover independent sources but, rather, comprises many varied and specialized publications and conference papers in new journals. This points to a strong core-periphery paradigm (with both specialization and interdisciplinary development in the research domain).

The collaboration trends among countries are depicted in the network visualization of VOSviewer, as in Figure 4. The size of the nodes is proportional to the number of published papers, and the edges represent the degree of collaboration between countries. The People's Republic of China is the most important node of the central area of the network and therefore has the greatest research output and collaboration influence in the network. China has significant ties to countries like India, Saudi Arabia, Pakistan, Australia, England, and the United States, reflecting its robust international research partnerships. India too has excelled in forging strong bonds with the members of the Asian community. The color-coded clusters show the confluence clusters of regional or thematic clusters. The density of the connections within the clusters is higher, and the density of the connections among the clusters or shared connections is lower. Some countries are on the edge, with fewer links, and therefore less output of research or less cooperation. From here, the map depicts a more interconnected global research environment with strong regional collaborations. China is the main influence.

The VOSViewer network system of institutional collaboration is shown in Figure 5, where the size of the nodes represents the number of publications and the thickness of the links indicates the degree of institutional collaboration. The Islamic Azad University is the biggest and most central university, indicating that it is the university that provides the most significant research results and has close cooperation with the researchers. It is closely related to major universities like the University of Tehran, Semnan University, Shiraz University and Tarbiat Modares University and forms a dense core cluster. There are also color-coded clusters with certain collaboration groups likely based on geographical proximity and other common research interests. It shows less collaboration with foreign universities and other peripheral institutions that are not as strong or as closely linked to it. The core group bonds are strong, with good cooperation between the domestic institutions and some international links indicating increasing world efforts. In summary, the network framework suggests a highly centralized model of cooperation, where a few major universities are the main players in its establishment, and the central node (Islamic Azad University) is the means of research collaboration across the network.

Figure 6 shows the keyword co-occurrence network map developed using VOSviewer to illustrate the intellectual structure and thematic links in the research domain. The map consists of several linked clusters. The size of nodes reflects the frequency of appearance of keywords, and the strength of links reflects the degree of association between keywords, while colors correspond to distinct thematic The clusters. main themes of the optimum, renewable energy source, wireless sensor network, multilayer perceptron, Maximum Power Point Tracker (MPPT), bus, and power loss are the most prominent and impactful keywords from the literature. The orange cluster is mainly linked to machine learning techniques such as multilayer perceptron, ANFIS, predictors and modeling techniques. The blue cluster is for classification and diagnostic applications such as vector machines, decision trees, benchmark datasets and predictive analysis. The red cluster comprises studies about power systems and renewable energy such as buses, power loss, operating conditions and voltage stability and optimization. The yellow green cluster is characterized by wireless sensor network, path planning, energy efficiency and network performance. The purple cluster contains

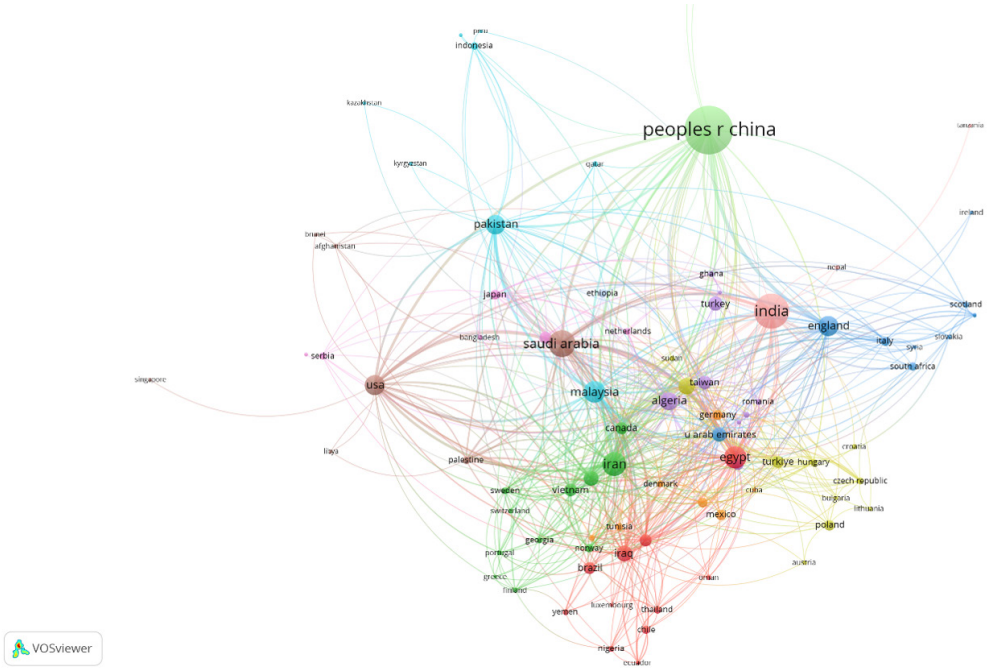

Figure 4: International Collaboration Network of Countries in Bat Optimization Algorithm Research.

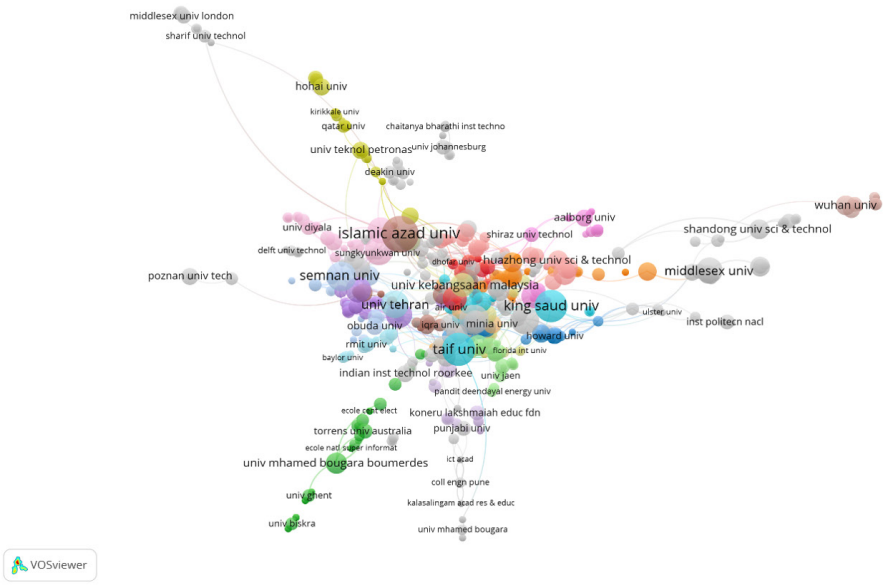

Figure 5: Institutional Collaboration Network in Bat Optimization Algorithm Research.

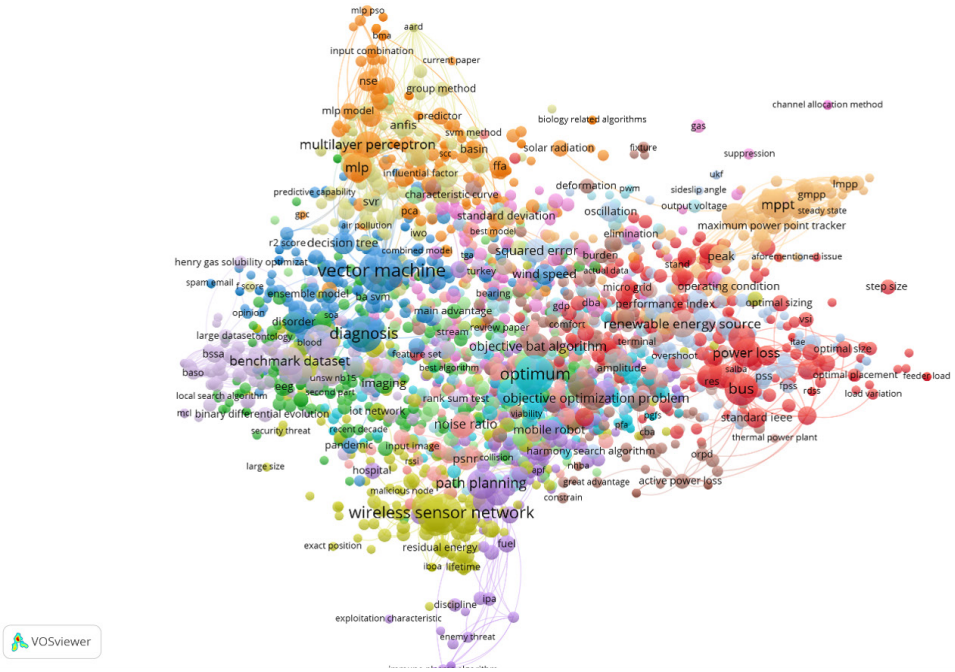

Figure 6: Occurrence of the Bat Optimization Algorithm.

security and optimization topics. The dense inter-cluster links show a high degree of interdisciplinary, which implies that artificial intelligence, optimization algorithms, renewable energy systems, sensor networks and diagnostic applications are getting more and more integrated within the research domain. The center of the word cloud contains keywords like "optimum" and "renewable energy source", suggesting that optimization-driven intelligent systems is a significant research area that connects the energy, communication, and machine learning domains. The network shows a mature and fast developing knowledge structure in general, with a large interaction between computational intelligence methods and engineering applications. This creates new opportunities for future research on sustainable, data-driven and intelligent systems.

Implications of Findings

The results of the research are of theoretical and practical importance. Theoretically, the research confirms the importance of Bradford's Law in identifying the main sources of publication in the research field of Bat Optimization Algorithm. The strong core-periphery structure suggests that the BOA research follows known bibliometric distribution patterns, despite the fact that it

is a rather niche and new research area. Practical implications the findings could assist researchers to identify key journals, prominent institutions and active collaboration networks. The identified core journals could be used by academic libraries for collection development and subscriptions decisions, and by researchers for potential publication outlets and collaborators. The study also offers a scientometric background of the future research on methodology.

CONCLUSION

The bibliometric analysis of the research about Bat Optimization Algorithm (BOA) from the year 2010 to 2025 shows how the concept has grown from the emerging idea to one of the most popular and widely used methods. The annual scientific production has experienced a steady increase with an upward trend since 2015, reaching peak values between 2022 and 2023, concomitantly with the increasing global interest in BOAs and their applications. There is a small decrease in publication output in 2024-2025 but overall, the trend still points to sustained academic interest and growth in BOA research. However, the citation patterns show that the pioneering studies had a high average citation, which demonstrates their important theoretical and methodological influence. In recent years citations have become stable. This is due to the maturing of discipline and the expansion of divisions into various areas. The analysis presented significantly highlights the core-periphery framework of the main analysis in line with Bradford's Law. Specifically, most of the publications revealed that the journal is situated in some high-impact engineering and interdisciplinary journals. At the same time, the large number of niche journals and conference publications reflects the variety of interdisciplinary topics (artificial intelligence, energy systems, control engineering, robotics, sustainability, and healthcare). The structural analysis shows that the core-periphery structure of the Bat Optimization Algorithm (BOA) research network is extremely strong. Such a configuration is of considerable practical utility to individual researchers and educational institutions. It is a central repository of knowledge for researchers and early career people. Because most of the progress in BOA is made by only a few leading authors, organizations and journals, newcomers do not have to go through the hassle of sorting through many scattered documents. They can concentrate their literature reviews on this particular 'core zone' to get up to speed on cutting-edge methodologies quickly. Furthermore, the knowledge of the most connected core researchers provides a useful guideline for authors to establish strategic networking and potential research collaborations. Such understanding of the structure is useful for the scholars and university library boards in the allocation of resources. In general, BOA research has evolved from a theoretical realm to an accessible one. The discipline is growing; international collaboration is increasing and thematically it is diversifying. Future works can focus on hybrid optimization models, real-time optimization methods, machine learning integration and smart manufacturing systems to further advance the BOA research landscape.

ABBREVIATIONS

ANFIS: Adaptive Neuro-Fuzzy Inference System; **BA:** Bat Algorithm; **BOA:** Bat Optimization Algorithm; **FOPID:** Fractional-Order Proportional-Integral-Derivative; **GA:** Genetic Algorithm; **MPPT:** Maximum Power Point Tracker; **PSO:** Particle Swarm Optimisation; **VOSviewer:** Visualization of Similarities viewer.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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