

BAT ALGORITHM: A DECADE OF DEVELOPMENTS, VARIANTS, APPLICATIONS, AND OPEN RESEARCH CHALLENGES

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Abstract

The Bat Algorithm (BA), introduced as a nature-inspired metaheuristic based on idealized echolocation, has developed into a family of continuous, binary, discrete, multi-objective, modified, and hybrid optimization methods. This survey reviews the decade from 2015 to 2025, emphasizing how researchers have addressed exploration–exploitation balance, premature convergence, parameter sensitivity, scalability, and problem-specific representations. The review synthesizes survey papers and representative applications in engineering design, power and energy systems, image processing, medical analytics, feature selection, classification, clustering, scheduling, routing, and other combinatorial problems. Particular attention is given to binary and hybrid BA variants because they connect continuous search operators to discrete decision spaces. Work by Dharmpal Singh on a modified bio-inspired BAT algorithm is included as a relevant research contribution, while his related work on evolutionary and swarm-intelligence methods for sentiment analysis is treated as application context rather than evidence that BA itself was evaluated on that task. The literature indicates that BA remains attractive for its simple structure and adaptability, but performance claims are highly dependent on benchmark choice, parameter settings, computational budget, and statistical validation. The paper concludes with a research agenda emphasizing reproducibility, fair comparisons, robust multi-objective design, explainability, and application-specific validation.

Keywords: Bat Algorithm; bat-inspired optimization; metaheuristics; binary optimization; hybrid algorithms; feature selection; literature survey

1. Introduction

Nature-inspired metaheuristics are widely used for optimization problems where exact methods are expensive or where the search landscape is nonlinear, discontinuous, multimodal, or constrained. Yang's original Bat Algorithm models simplified echolocation behaviour through frequency, velocity, position, loudness, and pulse-emission rate [1]. The algorithm has since been modified for continuous numerical optimization and adapted to binary, discrete, and multi-objective problems. Early surveys established the main families of applications and variants [2], while more recent reviews consolidated evidence across a much wider literature [3–5].

This survey focuses on the ten-year period 2015–2025. It is a narrative literature survey based on accessible review articles and representative primary studies, not a preregistered systematic review or a claim that every paper published in the period has been enumerated. The objective is to organize the main directions, identify recurring limitations, and provide a practical research agenda.

2. Review Scope and Method

The review prioritizes peer-reviewed surveys and representative research on BA variants, hybridization, feature selection, engineering optimization, energy systems, medical and image applications, scheduling, and network problems. Searches and bibliographic checks used accessible scholarly records, publisher pages, and indexed review articles. The period is 2015–2025 inclusive; earlier foundational papers are cited when needed to explain the algorithm's origin. A citation is not interpreted as proof that a method is universally superior. Application results are dataset- and configuration-dependent, and direct numerical comparisons are not made

where studies use different benchmarks or evaluation protocols.

3. Core Algorithm and Main Design Choices

In the canonical BA, each candidate solution has a position and velocity. A frequency parameter influences velocity updates; local search around promising solutions is controlled by loudness and pulse rate. These mechanisms aim to balance global exploration and local exploitation. However, the standard formulation leaves important choices to the practitioner: parameter initialization, bounds handling, stopping criteria, local-search intensity, and the mapping between continuous positions and the target decision representation [1–3].

These choices become especially important in high-dimensional or discrete tasks. A binary feature-selection problem requires a mapping from a continuous position to a bit vector. A scheduling or routing problem requires permutation or discrete operators that preserve feasibility. A constrained engineering task requires constraint handling or repair. Consequently, a BA variant should be described by its representation, operators, parameter adaptation, constraint handling, and evaluation budget—not merely by the name of the algorithm.

4. Evolution of BA Research, 2015–2025

The literature of the decade can be summarized as a progression from task-specific adaptations toward broader benchmarking, hybridization, and critical assessment. The 2015 survey by Chawla and Duhan reviewed applications and variants reported at that time [2]. Studies published around 2017–2021 increasingly explored binary and modified BA, hybrid strategies, and specialized operators for feature selection, image analysis, energy systems, and engineering

design. The review by Alyasseri and colleagues examined research from 2017 to 2021 and categorized applications and versions, including binary, modified, hybrid, and multi-objective forms [4]. Agarwal and Kumar provided a systematic review focused on theoretical foundations, variants, and applications [3]. Shehab and colleagues subsequently offered a comprehensive review of variants, applications, hybridization, limitations, and future directions [5].

Across these reviews, a recurring pattern is that no single BA variant is best for every problem. Improvements often arise from combining BA with local search, differential evolution, chaotic sequences, opposition-based learning, mutation, or domain-specific heuristics. These additions may improve search on selected benchmarks, but they also increase parameter count and make attribution difficult: a reported gain may arise from the added operator, the parameter tuning, or a larger computational budget.

5. Major Variant Families

5.1 Modified and adaptive BA

Modified versions change update equations, initialization, inertia-like controls, or parameter schedules to reduce premature convergence and improve search diversity. Adaptive strategies attempt to adjust exploration and exploitation during the run rather than relying on fixed settings. A strong evaluation should compare such variants under equal objective-function evaluation budgets and report variability across independent runs.

5.2 Binary and discrete BA

Binary BA maps candidate solutions to 0/1 decisions and is relevant to feature selection, subset selection, and knapsack-type problems. Discrete BA adapts the representation to permutations, schedules, routes, or other structured decisions. Transfer functions and repair mechanisms can materially change outcomes; therefore, authors should state them explicitly and test sensitivity to alternative mappings.

5.3 Hybrid BA

Hybrid approaches combine BA with algorithms such as differential evolution, particle swarm optimization, genetic operators, local search, or problem-specific heuristics. The intended benefit is to complement BA's search dynamics with stronger mutation, diversity, or local improvement. To establish that hybridization is responsible for gains, ablation studies should remove each added component and compare evaluation counts, runtime, and solution quality.

5.4 Multi-objective BA

Multi-objective variants aim to approximate a Pareto front rather than a single best solution. Typical design choices include dominance-based selection, external archives, diversity preservation, and indicators such as hypervolume or spread. Comparing multi-objective algorithms requires

consistent reference points, normalization, repeated runs, and suitable indicators rather than relying on one objective value.

6. Application Areas

6.1 Engineering, power and energy systems

BA has been applied to engineering design and power-system problems, including economic dispatch, controller tuning, renewable-energy optimization, and structural design. Reviews report broad interest in power and energy applications, but comparisons remain difficult because constraint models, load cases, and objective functions vary substantially [4,5]. Credible studies should publish constraints, test cases, feasibility rates, and objective-evaluation budgets.

6.2 Image processing and medical analytics

Image thresholding, image and signal processing, medical classification, and disease-related prediction appear repeatedly in BA review literature [4,5]. In these tasks, BA is often used to optimize thresholds, select features, or tune a classifier. Medical applications require careful separation of training and test data, external validation where possible, class-imbalance-aware metrics, and safeguards against feature-selection leakage.

6.3 Feature selection and classification

Feature selection is a natural use case for binary BA because a subset can be represented as a binary mask. Wrapper methods evaluate a candidate subset through a classifier and combine predictive performance with a penalty for subset size. This can be computationally expensive, particularly when the feature space is large. Filter baselines, repeated nested validation, selected-feature stability, and transparent computational budgets are needed to determine whether the optimizer contributes value.

6.4 Scheduling, routing, and network optimization

Scheduling, routing, wireless and network design, and other combinatorial problems require discrete representations and feasibility-preserving moves. In such settings, a continuous BA implementation cannot simply be thresholded without considering the problem structure. Domain-specific encoding and repair operators should be reported, and comparisons should include established problem-specific baselines.

7. Research Contributions Related to Dr. Dharmpal Singh

Singh's paper "A Modified Bio Inspired: BAT Algorithm" is relevant to the development of modified BA approaches [6]. Its bibliographic record identifies a modified bio-inspired BAT method and reports comparisons with benchmark algorithms. The complete numerical tables from that original article should be checked directly before reproducing any score or claiming a quantitative advantage. Singh and collaborators have also published work on a modified firefly algorithm for sentiment analysis and a genetic-algorithm-based approach to social-network tweet perception [7,8].

These papers demonstrate related experience with swarm/evolutionary methods and sentiment tasks; they should not be misrepresented as BA experiments.

8. Cross-Cutting Limitations

Several limitations recur across the literature. First, BA performance is sensitive to initialization and parameter settings. Second, convergence to a good solution does not guarantee global optimality. Third, hybrid variants can add complexity and make it difficult to identify the source of improvement. Fourth, studies may use different benchmark suites, stopping rules, or computational budgets, preventing fair comparison. Fifth, some papers emphasize the best run rather than distributions across repeated runs. Finally, real-world application papers may lack external validation, ablation studies, released code, or sufficiently detailed data-processing procedures.

9. Recommendations and Open Research Questions

Future studies should: (i) release source code, seeds, and full parameter settings; (ii) compare methods under equal function-evaluation budgets; (iii) report mean, standard deviation, confidence intervals, effect sizes, and appropriate paired tests; (iv) include ablations for hybrid components; (v) evaluate robustness to noise, dimensionality, and changing environments; (vi) design interpretable constraint handling for discrete problems; and (vii) validate on independent real-world datasets. For feature selection, reporting only accuracy is insufficient; macro-F1, balanced accuracy, subset size, runtime, and selection stability should be included. For multi-objective work, use multiple Pareto-quality indicators and transparent reference points.

10. Conclusion

The decade 2015–2025 saw the Bat Algorithm mature from a general nature-inspired optimizer into a diverse family of modified, binary, discrete, adaptive, hybrid, and multi-objective methods. Survey literature documents applications in energy, engineering, medical analytics, image processing, feature selection, scheduling, and network optimization. At the same time, algorithmic diversity makes rigorous comparison more important: improvements must be supported by fair budgets, repeated experiments, statistical analysis, and reproducibility. Dr. Dharmpal Singh's modified BAT work is a relevant contribution to this landscape, while related evolutionary sentiment-analysis studies provide adjacent application context. The next stage of BA research should prioritize robust evaluation and transparent evidence over adding complexity alone.

Table 1. Overview of BA literature surveys relevant to the 2015–2025 period

Ref.	Author(s) and year	Research focus	Relevance to the present study
[1]	Yang (2010)	Original Bat-Inspired Algorithm	Establishes the foundational BA method.

[2]	Chawla and Duhan (2015)	Survey of the state of the art in BA	Provides an overview of BA research and applications.
[3]	Agarwal and Kumar (2021)	Theoretical foundations, variants, and applications of BA	Supports examination of BA development and methodological variants.
[4]	Alyasseri et al. (2022)	Recent advances, versions, and applications of BA	Contextualizes developments in BA research.
[5]	Shehab et al. (2023)	BA variants, applications, and hybridization	Supports examination of hybrid and modified approaches.
[6]	Singh (2018)	Modified bio-inspired BAT algorithm	Directly relevant to modifications of the original BA.
[7]	Jana et al. (2024)	Modified Firefly Algorithm and sentiment-analysis approaches	Illustrates modified metaheuristics in sentiment analysis.
[8]	Radha et al. (2023)	Genetic Algorithm-based analysis of social-network tweets	Related work on evolutionary optimization for social-media analysis.
[9]	Singh (2017)	Metaheuristic-based information extraction	Relates metaheuristics to information extraction.
[10]	Purkait and Singh (2017)	Statistical and soft-computing methodologies for error optimization	Provides related optimization context.
[11]	Singh (2021)	Bio-inspired Social Spider Algorithm	Represents another bio-inspired optimization method for comparison.
[12]	Jana et al. (2024)	Hybridized analysis of public perception from COVID-19 tweets	Illustrates related sentiment-analysis research.

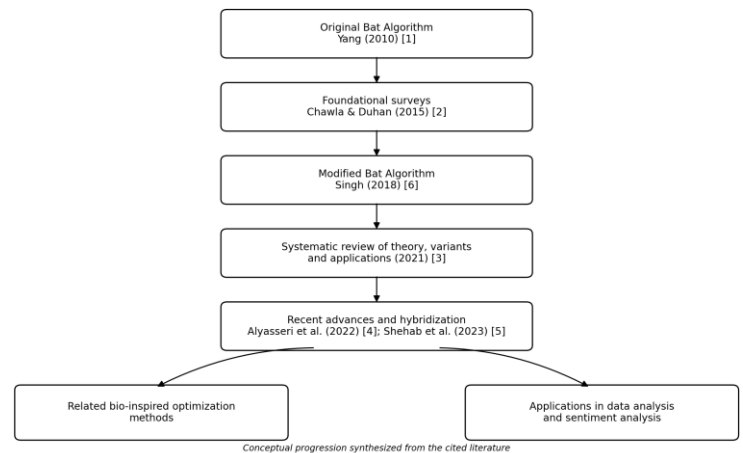


Figure 1. Evolution of Bat Algorithm research and its application areas

The literature traces the development of the Bat Algorithm from its original formulation to later surveys, modified variants, and broader

applications. Chawla and Duhan (2015), Agarwal and Kumar (2021), Alyasseri et al. (2022), and Shehab et al. (2023) provide context for understanding the algorithm's development. Singh (2018) contributes directly to modified BA research, while related studies on the Firefly Algorithm and Genetic Algorithm illustrate the wider use of metaheuristic optimization in data analysis and sentiment analysis. This literature motivates further investigation of algorithmic modifications and their empirical performance, which should be evaluated using clearly defined benchmark datasets, comparative baselines, and statistical tests.

Survey	Coverage / emphasis	Use in this review
Chawla & Duhan (2015) [2]	State-of-the-art survey; applications and variants	Early-period baseline
Agarwal & Kumar (2021) [3]	Systematic review of foundations, variants and applications	Taxonomy and theory
Alyasseri et al. (2022) [4]	Research from 2017–2021; variants and application domains	Decade trend synthesis
Shehab et al. (2023 issue; online 2022) [5]	Comprehensive review of variants, applications, hybridization and limitations	Recent synthesis and gaps

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