




# A survey and recent advances in black widow optimization: variants and applications

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## Abstract

Artificial Intelligence techniques, such as optimization algorithms, have become essential for success in many fields. Therefore, most researchers, especially in computer and engineering sciences, focused their efforts and abilities on adapting the optimization algorithms for solving various problems. This review introduces one of the recent nature-inspired optimization algorithms, called black widow optimization (BWO). This review highlights the main procedures of BWO, its strengths and weaknesses, the growth of BWO, the variants of BWO ( i.e., binary, modification, and hybridization), and the efficiency of BWO in different fields and applications (i.e., feature selection, medical, image processing, engineering, IoT, power and energy, and networks). As a result, the review seeks to assist researchers who are interested in using the BWO to address their challenges. For instance, it could help manage large pilgrim crowds, enabling smoother ritual performances and overcoming potential difficulties they encounter. Also, it suggests new possible ways of enhancing the efficiency of the basic BWO.

**Keywords** Artificial intelligence · Nature-inspired optimization algorithms · Black widow optimization · Optimization problems

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# 1 Introduction

The nature-inspired optimization algorithms proved their efficiency in dealing with various problems in different fields, such as Networks [18], Energy systems [79], Engineering [120], Medical field [55], and so on. These algorithms can be structured to find the most favorable solutions, either maximum or minimum, based on the fitness functions required. Figure 1 illustrates the two primary categories of search mechanisms: Firstly, heuristic algorithms, also termed single solution-based, employ specific heuristic methods and primarily aim for local optimal solutions. Well-known heuristic algorithms, such as HC [56], DFS [106], and BFS [14]. Secondly, metaheuristic algorithms, known as population-based methods, possess adaptability to various optimization problems through parameter adjustments and operation modifications. Metaheuristic algorithms are typically categorized into four classes [110].

Social insect colonies and animal societies often serve as the inspiration for population-based algorithms, mirroring the collective behavior of swarming insects during seasonal migrations in search of resources or safety [52]. These methods are valued for their resilience in finding solutions and their adaptability to various problems. One of the newer population-based algorithms, introduced in 2020 by Hayyolalam and Kazem, is BWO [35]. It's worth mentioning that the BWO is inspired by the lifecycle of black widow spiders, including reproduction-style cannibalism, and sibling cannibalism.

The organization of this review is illustrated as follows. Section 2 presents the development of BWO in different research fields. A brief description of BWO's mechanism is shown in Sect. 3. The variants of BWO are shown in Sect. 4. The BWO's applications are presented in Sect. 5.

Fig. 1 Taxonomy of the optimization algorithms

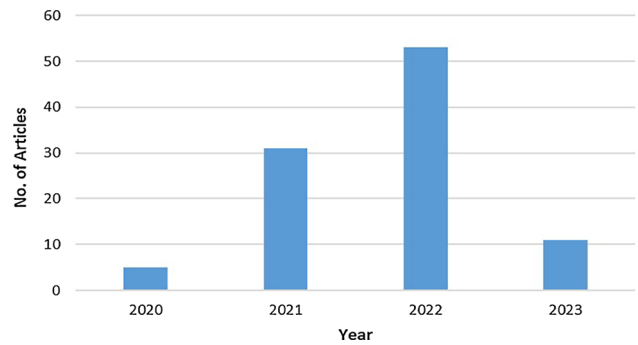
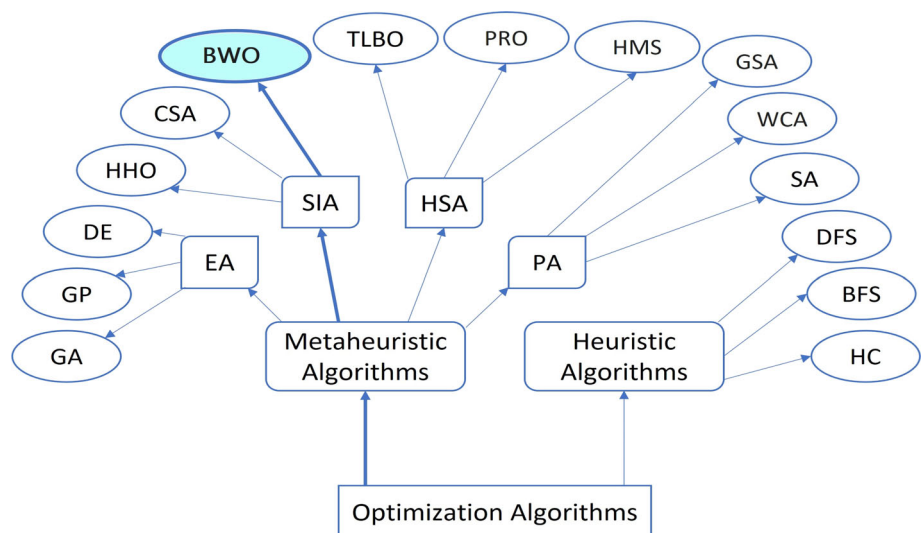


Fig. 2 Number of articles between 2020 and 2023

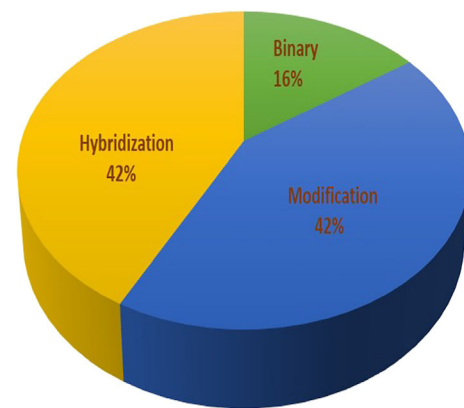


Fig. 3 Variants of black widow optimization

Evaluation and discussion are shown in Sect. 6. Finally, the conclusion and potential future directions are shown in Sect. 7.

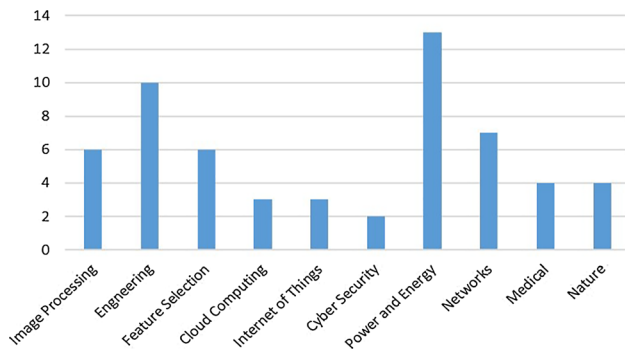


Fig. 4 Applications of black widow optimization

## 2 Data collection results

This section highlights the importance of Black Widow Optimization (BWO). It should be noted that the statistics in this section are based on the collected articles from common publishers (Springer, Elsevier, IEEE, and so on). Also, Google Scholar was used as a source to collect articles. The statistics classification started by showing how its use by researchers has increased since it was proposed by Hayyolalam and Kazem in 2020 until February 2023. Figure 2 illustrates the number of published articles during 2020, 2021, 2022 and 2023. The acceleration can be seen where it started with 5 articles published up to 100 articles by the first quarter of 2023.

The different versions of each algorithm indicate the iterations aimed at enhancing the initial algorithm. Figure 3 illustrates how articles are distributed across these variant types. For example, the majority of articles, 42%, focus on modifications, while another 42% concentrate on hybridization, with binary variants comprising 16%. This suggests that BWO presents ample opportunities for implementing diverse enhancements.

In addition, Fig. 4 demonstrates the BWO's effectiveness across various fields, notably excelling in Power and Energy research, followed closely by Engineering. Other fields showed a relatively equal distribution in publications.

The above statistics aid interested researchers in understanding the history of the BWO, as well as its strengths and weaknesses points. Thus, they can start their research, easily. More details will be described in the following sections.

## 3 Overview of black widow optimization

This section introduces an overview of BWO's inspiration from the life of black widow spiders. Also, it presents the formulation of the mathematical model in detail.

The BWO is a population-based metaheuristic inspired by the lifecycle of black widow spiders, including reproduction-style cannibalism, and sibling cannibalism. It imitates the mating behavior of black widows in structuring the mechanisms of exploring and exploiting the potential solutions' search space. It has the potential of fast convergence towards a global optimum solution while avoiding local optima stagnation problems. As stated by Hayyolalam and Kazem [35], it maintains a balance between exploration and exploitation procedures via a permutation process called "mutation." Like genetic algorithms and particle swarm optimization, the BWO structures a solution as "widow" compared to "chromosome" and "particle position." For some optimization problems, a potential solution is called "black widow spider" representing the values of the problem variables. Generally described the stages of the BWO:

1. Initial population: starting with generating an initial population of spiders representing potential solutions. A solution is represented in a one-dimensional array.
2. Evaluate the fitness of individuals: the fitness of each individual spider is evaluated by a fitness function depending on the problem-solving specifications.
3. Randomly select parents: if the stopping condition is not met yet, a pair of mating spiders of parents are randomly selected,
4. Procreate: for all pairs of spiders in the population, each pair reproduces a new generation. This stage is repeated for a number equal to half of the widows in the population (e.g., number of pairs) while avoiding duplicated randomly selected widows.
5. Cannibalism: here in the new generation, three strategies (resembling neighborhood structures) are considered, and one of them will be applied. They are sexual; siblings; and baby spiders. All of which are determined by the fitness value. This stage is an exclusive one for the BWO. Where, solutions with inappropriate fitness are omitted from the new generation, thus leading to early convergence.
6. Mutation: each of the chosen solutions randomly exchanges two elements in the array controlled by calculating a mutation rate.
7. Update population: the search process is ended by updating the population with the new generation and selecting a global solution found so far.
8. Stopping condition: A stopping condition is set to whether to end the search process with the best solution found or proceed with further procedures (starting at stage 3 to stage 7) until the stopping condition. Three stop conditions are considered here, either a predefined number of iterations; passing several iterations with no improvement on the fitness value (e.g., quality) of the best widow (e.g., global solution) found so far; or

achieving optimality (e.g., if the optimal fitness values of solutions are known in prior).

From the literature, the obtained results for a variety of applications indicated that the BWO algorithm has outstanding advantages in different aspects such as early convergence and achieving optimized fitness value compared to other algorithms [47, 67, 133]. In addition, it has shown its capability of providing competitive and promising results compared to genetic algorithms, particle swarm optimization, artificial bee colony, and biogeography-based optimization. Another effective factor of the BWO is its essential parameter settings which include procreating rate (PP), cannibalism rate (CR), and mutation rate (PM). The parameters should be appropriately adjusted to improve the effectiveness of the algorithm in finding the best solutions. PP determines how many individuals should participate in procreate; this may control the production of new generations to provide further diversification and higher opportunity to explore the search space more precisely. CR omits inappropriate individuals from the population. It ensures high performance for the exploitation stage by transferring the search agents from the local to the global stage and vice versa. PM ensures the balance between the exploitation and exploration stage. It controls the transferring of the search agents (e.g., spiders) from the global stage to the local and eventually directs them toward the best solution. The practice assumes that the better tuning the amount of the parameters, the higher the chance for escaping a local optimum and the higher the ability to explore the search space globally as well. Hence, the right number of parameters can ensure the controlling of the balance between the exploitation and exploration stages. Still, this needs more control along with the selection mechanism aka. cannibalism. Those three parameters are not enough in many cases. This is problem-dependent and leads to an undetermined global setting of the BWO across different optimization or engineering problems, where each problem has its own specifications, constraints, limitations, and solution representations. This makes the BWO predict its performance, behavior, effectiveness, or efficiency. Therefore, this study identifies the common effective stages and/or parameters used for the BWO in the literature and identifies the limitations of those stages and parameters.

## 4 Recent variants of black widow optimization

### 4.1 Binary of black widow optimization

Al-Saedi and Mawlood [5] developed an improved version of the Binary Black Widow Optimization (IBBWO)

method to tackle feature selection problems. The main objective was to reduce the number of selected features while preserving high accuracy. The developed approach combines BBW with a hill climb algorithm (HCA) to enhance the convergence rate and exploitation capability. The proposed approach is tested on twenty-eight benchmark datasets offered by UCI. The results demonstrated that IBBWO outperforms BBWO as well as the other six FS algorithms, including BMFO, BBAT, BGWO, BMVO, BWOA, and BPSO.

Kelecs and Kiliç [51] offered a Binary Black Widow Optimization (BBWO) for the feature selection problem. The authors aimed to eliminate the number of selected features and enhance classification performance in terms of accuracy, fitness value, and convergence curve. The effectiveness of BBWO was compared to four optimization techniques, including BPSO, VPSO, BGWO1, and BGWO2. The findings showed that, among 20 benchmark datasets from the UCI repository, BBWO offers the best convergence speed and fitness values in the majority of the datasets.

### 4.2 Modified versions of black widow optimization

A hybrid-modified BWO and PSO (MBWO-PSO) model was presented by Chaabane et al. [17] to enhance the effectiveness of blind spectrum sensing strategy for wireless communications. The authors aimed to overcome the early convergence issue and enhance the ability of BWO. According to the results, the MBWPSO algorithm outperforms the original method as well as the well-known PSO, SA, HS, and BBO algorithms. The proposed algorithm additionally showed the best performance for the feature selection problem. To improve the intensification and diversification capabilities of the original BWO and prevent the search from falling in the local optima, Wang et al. [123] proposed a modified form of BWO by integrating it with DE and the random disturbance (RD) method, named BWDERD. The DE approach was used to cut out unnecessary exploration. The RD factor is utilized to enhance the BWO's local intensification performance and lessen the likelihood of achieving local optimum. When tested against a variety of optimization functions and engineering problems, the proposed approach performed better in terms of exploration behavior and convergence speed. Hu et al. [40] proposed another modified version of BWO by incorporating the Quadratic Interpolation (QI) and Wavelet Mutation (WM) methods, called QIWBWO. QI is used to increase convergence speed and solution accuracy, whereas WM is added to boost population variety and prevent the algorithm from entering a local optimum. The proposed QIWBWO is evaluated on a set of benchmark functions

and the CEC2017 competition suite. The results indicated that QIWBWO performed better than BWO, Rat Swarm Optimizer (RSO), Seagull optimization algorithm (SOA), Tunicate swarm algorithm (TSA), Harris Hawk Optimization algorithm (HHO), Archimedes Optimization Algorithm (AOA), and Aquila Optimization (AO) algorithm in terms of convergence rate, stability, and accuracy. Munagala and Jatoth [73] proposed a hybrid version of chaotic maps and BWO (ChBWO) to tune the parameters of the fractional order proportional integral derivative controller. The controller is subjected to various evaluations including step, load, robust, and Bode. According to the findings, ChBWO was able to provide step responses that were superior to BWO, PSO BBO, ABC, and GA approaches in terms of rising time and settling time. The proposed controller has demonstrated its effectiveness across all testing cases, producing a consistent and reliable response.

Jadhav and Vidarthi [43] presented a combined approach of BWO and new mating behavior (BWO-NMB) to minimize errors and power consumption. The concepts of scrambling and descrambling are being integrated to boost system throughput. The proposed approach was evaluated on two datasets, 4 lakh binary dataset and 5lakh of binary dataset. Results that were repeated revealed that the improved Antenna Selection (AS) through BWO-NMB had a lower symbol error rate (SER) than with AS and without AS. Similarly, the BWO-NMB model has a higher signal-to-noise ratio and a lower SER when compared to the BWO, Seagull Optimization (SOA), Rider Optimization (ROA), and Fitness Familiarized Lion Algorithm (FFLA). Semchedine and Bensoula [103] proposed a modification of BWO for solving numerical benchmark functions, called MBWO. Three major modifications were made in this study: removing sexual cannibalism and delaying the destruction of the father; employing opposite-based learning to develop good starting candidates during the algorithm's initialization step; and adaptively altering the probabilities of crossover and mutation. The reported results showed that MBWO surpasses the original algorithm as well as adaptive BWO (ABWO), Bio-geography-based optimization (BBO), GA, and invasive weed optimization (IWO).

In [28], the authors enhanced BWO (EBWO) for the production distribution problem in supply chain management. A mixed integer programming model was used to mathematically represent the optimization problem. The authors added the SA algorithm to BWO's mutation phase to improve EBWO's performance and balance its global and local search capabilities. A collection of test cases was taken from Solomon benchmark test problems, Gehring and Homberger benchmark test problems, and Taillard benchmark test problems. The results showed that the

proposed EBWO outperforms the GA, memetic algorithm (MA), and discrete artificial bee colony algorithm (DABC).

To speed up the convergence rate of BWO and prevent local optima, Wan et al. [121] offered an improved BWO algorithm (IBWOA). The authors used a variety of techniques to increase the search efficiency of BWO, including the differential evolution (DE) algorithm to reorganize the individuals with low fitness values and the elite opposition-based learning approach to speed up algorithm convergence. The authors also used the Gauss chaotic mapping to preserve the diversity of the initial solutions. The proposed approach was evaluated on six real-world constrained engineering problems and 13 benchmark functions from the CEC2017 test suite. IBWOA showed a significant improvement in terms of solution accuracy, performance, and convergence speed when compared to BWOA, HHO, CPSO, GWO, whale optimization algorithm (WOA), hybridized fruit fly bumble bee optimization algorithm (HFBOA), symbiotic organisms search (SOS), and salp swarm algorithm (SSA).

Hu et al. [41] proposed a method to optimize the conversion between Q-Bézier surfaces and rectangular Bézier surfaces. The proposed method combined the BWO with a golden sine learning strategy and diffusion process (LDBWO). The authors aimed to find better appropriate shape parameters to produce Q-Bézier surfaces that approximate the specified Bézier surfaces as closely as possible. The proposed algorithm employed a golden sine learning strategy and diffusion process to enhance the accuracy, speed up the convergence, and avoid falling into local optimum. The proposed LDBWO was evaluated on 35 benchmark functions and three complex engineering examples. The reported results showed the better performance of the LDBWO when compared to SOA, HHO, AOA, AO, TSA, RSO, SCA, GSA, slime mold algorithm (SMA), spotted hyena optimizer (SHO), and WOA.

Sheriba and Rajesh [115] modified the mutation step of BWO with the direction average strategy, named Boosted mutation BWO (BMBWO). The BMBWO was then enhanced further by the addition of a fuzzy logic system (BMBWFL) to enable the most effective cluster head node searches. After that, BMBWFL was combined with a hybrid energy-efficient distributed (HEED) protocol to select the higher residual energy. Twenty distinct benchmark functions were used to evaluate the proposed algorithm, and it was compared to existing algorithms such as PSO, ABC, TSA, BWO, BMBWO, ICFL-HEED, HEED, and ICHB-HEED.

Ayyasamy et al. [8] proposed a hybrid deep neural network with a modified BWO for aircraft auto-landing system to handle such kinds of accidents during the landing of the unmanned ariel vehicles and to ensure an exact landing path (HDRNN-MBWO). The main objective of the

newly developed method was to develop a reliable, smooth, and safe automatic landing system [15]. The BWO was modified to include a crossover operator alongside the mutation operation. The proposed algorithm performed more effectively and produced superior results when compared to the other four adaptive NN versions, including an adaptive neural output feedback controller (ANOF), adaptive neural state-feedback tracking controller (ANSTC), backpropagation network (BpN), and adaptive neural tracking controller (ANTC).

### 4.3 Hybridized versions of black widow optimization

A hybrid algorithm is composed of several algorithms to find an optimal solution for a problem. BWO is progressively garnering the attention of researchers from various fields all around the world. As a result, different applications and hybridizations of the fundamental BWO have emerged.

Manikandan et al. [63] proposed a Hybrid Black widow and Fish Swarm Optimization Algorithm (BWFSO) For resource distribution and job scheduling in cloud computing. To improve cost, power, and resource usage, the authors suggested a combination fuzzy C-means clustering technique that uses fish swarm optimization for resource distribution efficiency and BWO for job scheduling. The proposed method output is compared to previous algorithms in the field, demonstrating that the latter has some drawbacks while the former has some advantages. The proposed method performed well in terms of time, power, and cost.

For the Traveling Salesman Problem, a hybridization of BWO and Variable Neighborhood Descent (VND) Algorithm is put out in [58]. The authors suggest two changes to the BWO method to address its limitations in the use of search space. The first change is the addition of VND, which improves the exploitation process by locating more nearby regions while the program is running. The second change concentrates on the reactive search process by incorporating a new convergence metric for the method during the program execution and online dynamic search process. The proposed method outperformed other optimization algorithms in the field in terms of minimal tour distance, proving that the suggested approach may be used to address a variety of optimization issues, such as the vehicle routing challenge, categorization, and clustering.

A hybridization between enhanced Butterfly Optimization Algorithm (BOA) and BWO named BWO-BOA is presented in [126] for feature extraction of network intrusion detection, that adds a reactive search plan to the global selection stage of BOA, employs the BWO method's mobility search strategy as the local search, and

simultaneously utilizes the small probability alteration technique to cut the redundancy to avoid the enhanced BOA from being stuck in local optima. The findings demonstrate that the suggested method may considerably improve the feature dimension reduction and improve the effectiveness of the attribute extraction model as applied to network intrusion detection.

In addition, for an energy-efficient clustering process, Sheriba et al. [114] presented the IIT2FLS-HEED (IHCBW with interval type 2 fuzzy logic system-based HEED) technique. The application of the IHCBW approach, which combines CS and IBWO, is to choose the best residual energy. Using IT2FLS (the interval type 2 fuzzy logic system), the ideal cluster heads are selected.

A method of displaying data outsourcing to a variety of different individuals is called crowdsourcing. Priya et al. [85] introduced a privacy-preserving model based on fuzzy with the BWO and SMO (Spider Monkey Optimization) named BW-SMO to address the issues with privacy-preserving crowdsourcing systems. The search solution can be clustered using the fuzzy. BW-SMO method took advantage of the BWO method combined with SMO optimizer to improve the query selection. The fuzzy logic controller controls the settings of both methods. Additionally, In [71], a Deep Convolutional Neural Network (DCNN) Learning model built on BWO was intended to recognize people and objects in video frames. With the aid of the BWO method, the hyper-parameters of the DCNN are best chosen. Preliminary processing was employed in the suggested technique to improve image quality in addition to eliminating distortion from the photos utilizing the Gaussian filter and noise removal.

Big data can manage various types of information and formats using a variety of cutting-edge technologies. Ravikumar and Kavitha [93] proposed a new big data analysis clustering method based on the HDFS distributed information management system's adaptive hybrid mutation BWO called AHMBWO. The suggested approach also highlights three distinct steps, including the creation of RDF (Resource Description Framework) graphs, an AHMBWO-based grouping method for a decentralized information management system in HDFS, and placement and partitioning for handling and controlling the distribution of data. The empirical research shows that, when compared to all other alternatives, the suggested method delivers good outcomes with shorter execution times.

Task scheduling has emerged as a popular area of research due to the rising need for cloud computing technologies. In [76] the authors put out a technique called ANFIS-BWO (Adaptive Neuro-Fuzzy Inference System-BWO) to cut down on the amount of time, money, and energy needed to complete activities that make good use of available resources. The suggested method uses a BWO

**Table 1** Summary of the BWO's variants

Variant	Abbreviation	Description	Area	References
Binary	IBBWO	Used to reduce the number of selected features while preserving high accuracy	Feature selection	[5]
	BBWO	Applied to eliminate the number of selected features and enhance classification performance	Feature selection	[51]
Modification	MBWO-PSO	Used to enhance the effectiveness of blind spectrum sensing strategy for wireless communications	Wireless communications	[17]
	BWDERD	Used to improve the BWO's capacities for intensification and diversification, and prevent the algorithm from stopping in the local optima	Optimization problems	[123]
	QIWBWO	Used to increase convergence speed and solution accuracy	Optimization problems	[40]
	ChBWO	ChBWO used to tune the parameters of the fractional order proportional integral derivative controller	Electrical power generation	[73]
	BWO-NMB	BWO and new mating behavior (BWO-NMB) are used to minimize errors and power consumption	Power system	[43]
	MBWO	Improving the initial population's quality and preserving a good balance between exploitation and exploratory capabilities	Optimization problems	[103]
	EBWO	Employed to address a variety of dataset problems related to the production distribution problem in supply chain management	Optimization problems	[28]
	IBWOA	Applied to speed up the convergence rate of BWO and prevent local optima	Optimization problems	[121]
	LDBWO	Used to optimize the conversion between Q-Bézier surfaces and rectangular Bézier surfaces	Optimization problems	[41]
	BMBWFL	Utilized for the energy-efficient clustering protocol for WSN	WSN	[115]
	HDRNN-MBWO	Employed for aircraft auto-landing system to handle such kinds of accidents during the landing of the unmanned ariel vehicles and to assure an exact landing path	Aircraft landing system	[8]
	Hybridization	BWFSO	Using BWFSO for resource distribution and job scheduling in cloud computing	Cloud computing
Hybridization of BWO and Variable Neighborhood Descent (VND) Algorithm for the Traveling Salesman Problem			Traveling Salesman Problem	[58]
Hybridization between enhanced BOA and BWO for feature extraction of network intrusion detection			Network Intrusion Detection	[126]
IIT2FLS-HEED		Improved hybrid cuckoo BWO energy-efficient clustering protocol	energy-efficient clustering	[114]
BW-SMO		BW-SMO, a privacy-preserving model based on fuzzy with the BWO and SMO	Privacy preserving-based crowdsourcing system	[85]
		Using a hybrid DCNN Learning model built on BWO to recognize people and objects in video frames	Human object detection	[71]
AHMBWO		AHMBWO, Big data analysis using an adaptive hybrid mutation BWO clustering-based data partitioning	Big data analysis	[93]
ANFIS-BWO		ANFIS-BWO, cut down on the amount of time, money, and energy needed to complete activities that make good use of available resources	Task scheduling	[76]
OBL-BWO		OBL-BWO to improve the suggested controller FOPID FF which is employed to enhance the efficiency of the CSTR system	CSTR system	[82]

combined with ANFIS method to quickly establish the right Virtual Machine (VM) for each task. Another key goal for making the best use of resources in the cloud infrastructure is resource scheduling. In the ANFIS scheme, the optimum solution is found using the BWO method. The suggested method can make use of the optimal server by scheduling the VMs there.

Prabhakaran et al. [82] suggested a new control system called FOPID<sup>2</sup>FF<sup>2</sup> to enhance the efficiency of the Continuous Stirred Tank Reactor-(CSTR) system which is a FOPID controller with dual fractional derivative filters in the two derivatives of fractional order. The suggested controller comprises 9 adjustable settings on their own that are improved using an optimization technique called OLBWO (Opposition-Based Learning with BWO). The OLBWO selects its starting population through OBL. The OBL increases the method's exploration ability, eliminates stuck-in local optima, and enhances the accuracy of the starting generation for the BWO. Table 1 shows a summary of the BWO's variants.

## 5 Applications of Black Widow Optimization

### 5.1 Feature selection

Daniel and Joseph [22] developed a hybrid technique that used BWO, machine learning and lexicon-based methods to achieve better accuracy and scalability of sentiment analysis. Many experiments of the technique show better results than other techniques like Genetic Algorithm (GA) and Particle Swarm Optimization algorithm (PSO).

In [69], the authors developed a black widow optimization algorithm (BWOA) with a K-means algorithm using a sum of Euclidian distances to enhance data clustering. The results of the technique that solved clustering problems showed better accuracy than other algorithms such as K-means and GA algorithms alone.

Hosseinalipour et al. [38] introduced a new technique called Multi-objective Opposition Binary BWO (MOBBWO) using the BWO algorithm to enhance text psychology in social networks. The technique used fifty implementations to evaluate the optimization function and degree of convergence, it experimented with many algorithms and attained good performance and better results in text psychology.

Hu et al. [42] the paper developed an algorithm called SDABWO using the BWO Algorithm called SDABWO to solve the feature selection problem; the algorithm calculates the distance between spiders and female spiders' weight, using of mutation operator of differential evolution. The technique improves convergence speed and

enhances the ability of exploitation. The technique conducts many experiments, the results show the capability of the technique to improve the accuracy of classification and reduce dataset dimensions.

In [31], the authors proposed a new technique called Novel Black Widow Meta-Heuristic Optimization (NBWMHO) technique using novel black widow (NBW) deep learning (DL) to improve speed and accuracy of web page classification, search engine algorithm, and spam filtering by reducing features of page structures; the technique tests many experiments and gets better results than other algorithms.

Dutta et al. [25] integrated the wrapper of feature selection (WFS) technique with the BWO to enhance the classification of data, the technique pre-processes data analysis to improve the performance and attain good results; many experiments compared with other techniques like Feature Selection using Genetic Algorithm (FSGA) and Feature Selection using Particle Swarm Optimization (FSPSO). The technique achieves better results in classification accuracy and features subset and is more suitable for large datasets.

### 5.2 Cloud computing

Cloud computing is a distributed computing infrastructure that delivers various computing resources through the network. Recently, several types of research based on natural-inspired algorithms have been proposed in the literature to improve the performance of the cloud computing environment. For instance, You et al. [128] proposed a new version of the BWO algorithm to solve the discontinuous optimization in workflow scheduling in the cloud environment by optimizing the procreate, cannibalism, and immutation phases, whereas Kumar et al. [60] proposed another scheduling algorithm based on the BWO, called (EEBWOSA), to reduce power consumption and maintain QoS in cloud computing.

However, in [70], the authors integrated the chaotic map with BWO to propose an efficient routing protocol called chaotic black widow optimization algorithm (CBWOA), in which the authors applied the chaotic maps to locate the finest map for the BWOA in big data access in the cloud computing environment.

Verma [119] introduced a novel hybrid optimization approach designed for secure task scheduling within cloud environments. It encompasses six key objective functions: makespan, execution time, Quality of Service (QoS), utilization cost, and security considerations. To achieve optimal results, the author proposed the BWO Combined Seagull Optimization (BWCSO) algorithm. As well as, utilizing the cycle crossover (CX) to generate offspring from parent elements, wherein each slot is filled by an



element from a different parent. The work concluded by evaluating the performance of the suggested algorithm and determining its superiority in optimizing makespan.

Kalai and Anandhakumar [48] introduced the HSRLBA, a method employing the Black Widow Algorithm for Reinforcement Learning. HSRLBA focused on resource allocation using BWA to swiftly converge parallel agents in the SARSA model within RL. The experiments were conducted using the Cloudsim simulator, evaluating the frameworks efficiency through Makespan, Task Completion Ratio (TCR), total energy consumption, response time, and resource utilization. HSRLBA yielded promising results: energy consumption of 325KWh, a response time of 15.42s, a Makespan of 1150s, TCR reaching 0.98, and resource utilization at 0.92.

### 5.3 Internet of things

The Internet of Things (IoT) connects an enormous number of devices which is expected to increase in the future [2]. However, the heterogeneity and openness of things and the limited resources make IoT suffer from several problems, like resource optimization, energy consumption, and routing of packets [7]. Therefore, Sharma et al. [105] proposed a lightweight version of the AODV protocol called Lightweight On-demand Ad hoc Distance-vector Routing Protocol-Next Generation (LOADng) protocol. Then, BWO was adopted to select the optimal parameters of the routing protocol.

Moreover, the Internet of Things-based Autonomous Vehicle Driver Scheme (IoT-ACDS) model proposed in [92] to design different scenarios obtained from the self-driving vehicle. Then, the ANFIS-BWO algorithm is applied to obtain the optimal value, which thus provides precise and safe vehicle operation control.

Cloud computing is an essential infrastructure of the Internet of Things for data analysis and storage, where an intermediary controls and manages the interconnected things in cloud computing and is called a cloud broker. Jelodari et al. [44] used a BWO optimization algorithm to maximize broker profit and system availability, as well as to minimize power consumption and the response time of users' requests.

Balakrishnan and Vinoth [11] introduced a new Hybrid Sine-Cosine Black Widow Spider Optimization Route Selection Protocol (HSBWSO-RSP) designed for Multihop Communication in IoT-supported WSN. The protocol aims to efficiently determine the most suitable routes for multihop communication. It integrated a variance perturbation mechanism into the traditional BWSO algorithm, allowing for enhanced route determination. Route selection relied on a fitness function involving both Residual Energy (RE) and distance (DIST). The HSBWSO-RSP technique undergoes

rigorous testing through various experiments, and the outcomes were evaluated across different metrics. Remarkably, the proposed methodology achieved notable results: a flawless 100% packet delivery rate, zero packet loss, and an end-to-end delay of 2.33 s. The comparative analysis demonstrated the superiority of the HSBWSO-RSP technique over existing routing methods.

The LOADng protocol, an extension of AODV, caters to resource-limited IoT networks seeking minimal routing control overhead and zero packet loss. Enhancing QoS in these environments hinges on fine-tuning routing protocol parameters. Therefore, Sharma and Jain [105] focused on optimizing LOADng parameters via the BWO algorithm tailored for IoT. Simulations highlight LOADng-BWO's superiority over conventional LOADng, showcasing reduced delay, overhead, and enhanced delivery ratio.

In [100], the authors developed an improved version of the BWO using the FEBWS-SERPPA, a Secure Encrypted Random Permutation Pseudo Algorithm. They aimed to facilitate better communication among IoT clusters by efficiently selecting cluster heads based on factors like energy usage, latency, and distance. The FEBWS-SERPPA algorithm significantly improves the BWO technique by ensuring the best cluster head selection within each cluster. The results demonstrated that the FEBWS-SERPPA algorithm outperformed existing methods, delivering faster performance, remarkably low energy consumption, and an extended network lifetime.

Vaiyapuri et al. [118] introduced CBR-ICWSN, an IoT-centered cluster-based routing protocol for wireless sensor networks. The authors employed a BWO technique to efficiently choose cluster heads and utilized an oppositional artificial bee colony method for optimal path selection. Through simulations, the CBR-ICWSN's performance was assessed, showing superior results in network lifetime and energy efficiency compared to other methods.

### 5.4 Cyber security

Peng et al. [80] proposed a hybrid optimization model consisting of the Butterfly Optimization Algorithm (BOA) and the BWO to overcome the improved BOA easily falling into a local optimum in the local search phase, takes advantage of the small probability mutation strategy to filter out the redundant features.

Moreover, BWO has been applied in other fields, such as intrusion detection systems (IDS). For example, Kanna et al. [50] proposed a smart hybrid IDS model called (BWO-CONV-LSTM). The system consists of two phases. In the first phase, an artificial bee colony (ABC) is used for feature selection. During the second phase, a hybrid model of BWO and neural network classifier CONV-LSTM is

applied to the MapReduce framework to detect intrusion from the network traffic data.

While cloud computing provides many useful features to users as mentioned earlier, it also comes with several security issues, such as data breaches and attacks that may disrupt service providers, causing the entire system to fail. Therefore, in [104], the authors proposed a hybrid solution called BWO-RNN to secure data in the cloud environment from hackers, in which the authors used the BWO feature selection algorithm to simplify the classification process that is performed using RNN to determine whether an attack has occurred or not.

## 5.5 Engineering

Vijayakumar and Suresh [120] employed a streamlined strategy utilizing deep learning techniques to reduce cycle time. Firstly, the current organizational structure is assessed through Value Stream Mapping (VSM). Subsequently, a Modified Deep Belief Neural Network is employed to identify instances of excessive time consumption. This modification involves optimizing weight parameters using the BWO. Identified excess time is then targeted for elimination, aiming to enhance profitability. The simulation of the BWDBN approach was analyzed, comparing predicted values against actual results. Results showed impressive accuracy, precision, and recall of 98%, 97%, and 96.5%, respectively, indicating the potential for novel product design and increased profits through the BWDBN approach.

In [57], the authors proposed a multi-objective hybrid technique named black widow-bear smell search algorithm (IBWBSA) using the BWO to improve the speed of convergence with the search strategy bear smell search algorithm (BSSA). The technique aims to achieve optimal operation and planning for distributed generators (DGs) by reducing voltage deviation, power loss, and generation cost by optimally operating and planning the distribution system (DS); the technique shows more effective results than other techniques.

Bashir et al. [12] used a modified Akima piecewise cubic Hermite interpolation (Makima) technique and the BWO algorithm and computational fluid dynamics simulation; the technique aims to improve the design of camber morphing airfoil of Unmanned Air Systems (UAS-45) wing and maximizing the ratio of lift-to-drag. The technique results in increased ratio of lift-to-drag from 48.53 to 86.52 relative to a baseline optimized airfoil at climb and cruise flight conditions.

Micev et al. [67] used the BWO algorithm and field waveform of the short-circuit test. The technique identifies synchronous generator parameters nested in the standard graphical method using test data of sudden short-circuit to

estimate parameters of the synchronous machine by minimizing the sum of squared errors (NSSE) between experimental and simulation results. The technique tests many experiments compared with other algorithms such as BWO, GWO, HHO, and HGSO.

Gubbala et al. [32] utilized the Self Adaptive Levy flight-based Black Widow Optimization (SALBWO) algorithm to locate the optimal size and location of Distributed Generation (DG). The technique found that the distribution network can be operated with the maximum benefit of Distribution Companies (DISCO's) considering the correct size and location of the DG modules; it is used also to operate and extend the distribution network considering the load modeling impact.

In [132], the authors developed an algorithm called Sobol sequence initialized black widow optimization algorithm (SBWOA) for improving robustness, global optimality, and randomness of the optimization algorithm comparing with gradient descent algorithm (GD) and stochastic gradient descent methods (SGD). The technique was verified by many experiments and showed proposed results.

Samal et al. [98] used the BWO algorithm and load flow to reduce loss of power in distribution systems. The technique also investigated voltage magnitudes, the effect of Distributed Generation (DG) algorithm mode on the device's total reactive power loss, and loadings of individual branches, the technique determined solutions for steady-state power flow solutions, and the results showed lower total active power loss compared to other technologies.

Munagala and Jatoth[72] developed a fractional order proportional integral derivative (FOPID) technique for automatic voltage regulator (AVR) system using metaheuristic BWO for tuning controller, reducing produce stable voltage and fluctuations The technique improves rise and settling times of the system and shows better results than other algorithms using GA, CS, C-YSGA, and PSO.

## 5.6 Power and energy

A unique bio-inspired metaheuristic BWO algorithm was presented in [79] to solve the economic load dispatch problem. The proposed method ensures exploration and exploitation by mimicking the spider's distinctive courtship and mating behavior. CEC 2019 and two separate test systems were used to evaluate the efficiency of BWO. The results illustrated that BWO outperformed the other algorithms.

Li et al. [61] proposed a new polymer electrolyte FC (PEFC) design model utilizing a through-plane array, and some of the model's unidentified parameters were established using a cutting-edge optimization procedure. The optimal flow field model has been determined by solving

the optimization problem. This approach has been used to determine the ideal value for the unidentified parameters after demonstrating the suggested model's superiority over another flow field.

In [99], the authors presented an improved LLC-RC that can lower system error by optimizing the output voltage and resonant inductor current by utilizing the BWOA technique. The performance capability of the proposed model was determined scientifically from the results of the trial.

The voltage-control loop was created using an automated voltage regulator [96]. Additionally, a hybrid system linear model with coordinated voltage and frequency control has been developed. Different load disturbances and various reactive loads are examined for dynamic frequency response and voltage deviations. The BWO method is used to determine the gains of the SG and static volt-ampere reactive compensator (SVC) controllers in the IG terminal.

In [102], the energy storage technology for compressed air, which stores electricity as compressed, high-pressure air, is employed. To address these power quality problems, a controller is added to the system. The Unified Power Quality Conditioner (UPQC) is employed. To balance out the voltage and current that are out of balance, UPQC injects actual power into the transmission line. Based on BWO, the controller optimal gain value is correctly chosen. Also, the WT emulator makes use of a permanent magnet direct current motor supplied by a DC-DC converter that has been optimized using the BWO method [83].

A reliable pheromone value BWO technique (pv-BWO) is suggested to determine the correct modeling parameters of solar PV [20]. The suggested technique demonstrates the elimination of early conversion to local minima and offers a more optimal approach to the issue. The computing cost also decreases as a result of the suggested methodology's strong convergence ability. The goal in [21] is to manage the frequency of a photovoltaic integrated power system. This is done by employing a tuned proportional integral and proportional integral derivative controller that has been optimized using the BWO algorithm's unique cannibalism feature. Under the partial shading condition, a global maximum power point tracking control approach based on the BWO is suggested [27]. The research's authors asserted that the control algorithms they suggested had great control effects, primarily manifested in their quick reaction time, low fluctuation, stable control, and excellent output parameters (current, voltage, power, duty cycle). The results show that the algorithm tracks accurately and exhibits minimal power fluctuations. As a result, the method may decrease energy loss and increase PV power generation efficiency when there is partial shadowing. Pheromone Value BWO (pv-BWO) and Cannibalism BWO (cn-BWO) are the authors' two suggested

approaches for thorough modeling [19], as well as for estimating the parameters of solar PV. According to the authors, pv-BWO provides a dependable and accurate solution to the parameter estimation issue with the least cost function, whereas cn-BWO exhibits a higher rate of convergence. With increased contributions to power quality and system efficiency, a distributed generation technology is used to reduce active power losses in the distribution lines [95]. BWO approach is used to identify the position and capacity of several DGs. The Load Impedance Matrix approach is used for power flow analysis to determine system bus voltages, current flow, and power losses in the lines. Also, the author proposed an improved technique for Loss Reduction using BWO which is used at the distribution networks reconfiguration [64]. The best size of a stand-alone hybrid energy system (HES) including solar PV, wind turbines (WT), diesel generators (DG), and energy storage has been done in this study [116]. BWO is used to discover the best HES size through energy management utilizing sample day load data and an annualized model.

## 5.7 Networks

Wireless Sensor Network (WSN) is used in a wide range of applications. However, it has many challenges, like finding the best path for delivering packets in WSN with minimal energy consumption. Therefore, [18] adopted BWO to propose a reliable and optimized routing protocol that can select the best path and, at the same time, deliver data securely with minimal power consumption by selecting a secure Cluster-Head Selection for WSN.

Another difficult problem facing designing an effective WSN is the deployment problem. Therefore, Deghbouch et al. [23] enhanced for BWO to propose a new deployment algorithm called Enhanced BWO (EBWO), which aims to select the least number of deployed sensors that provide the optimal coverage with minimal cost. To achieve this goal, the proposed EBWO optimizes the searching capabilities and the running time of the algorithm by modifying the reproduction phase and applying a chaotic initialization to enhance the exploration ability of the initial population.

Moreover, the node capture attack is a severe attack in WSN, in which the intruder can easily penetrate the entire network and steal secret data. Khare et al. [54] exploited the capabilities of the BWO optimization algorithm to develop a model that enhances the WSN protection by detecting the sensor vertices' superior compromise potential by attack.

## 5.8 Image processing

Recently, image processing has been employed in many different fields, including face identification, medical diagnosis, remote sensing, and traffic. Each of these apps often performs several image processing-related techniques on photos to improve our comprehension of the images [88]. In applications involving image processing, segmentation is an essential stage. This method divides the image's cells into several groups, allowing for the examination of the objects. The method that does this goal most readily is multilevel thresholding; the challenge is in determining the best thresholds to accurately separate every image. Finding the optimal thresholds is aided by methods like Otsu's between-class variance, although they are computationally expensive when there are multiple thresholds.

In order to get around the drawbacks of multilevel thresholding techniques, the BWO method has been employed more than once [4, 39, 45]. Houssein et al. [39] presented the application of the cutting-edge meta-heuristic BWO method to identify the ideal threshold setting of a grayscale image by utilizing and combining Otsu and Kapur as the fitness function. The Kapur's and Otsu's algorithm's optimal thresholds are to be found using the BWO method. In consideration of objective function value in addition to other performance metrics like peak signal-to-noise ratio (PSNR), structure similarity index (SSIM), and feature similarity index (FSIM), the testing findings showed that the proposed method outperformed the rival methods. Comparing the proposed method to other approaches already being utilized in the field, it was discovered to be the most promising method.

Additionally, Al-Rahlawee et al. [4] proposes yet another use of the BWO approach to determine the ideal threshold of a multilevel threshold problem. Each threshold in the suggested approach is a part of a dimension of the BWO method solution, and an effort is made to use this method to determine the ideal threshold level with a low level of complexity. The suggested approach demonstrates a strong capacity to threshold clinical data, including the detection of optic disks and brain malignancies. Furthermore, a novel multilevel thresholding approach employing BWO is also suggested in [45]. To determine the best threshold levels, the study attempts to improve six distinct fitness functions, including Otsu's between-class variance, Tsallis entropy, Masi entropy, Kapur's entropy, Renyi's entropy, and fuzzy entropy. The results of the experiments reveal a considerable improvement in the suggested method's ability to segment both grayscale and color images.

An intelligent Image Enhancement with a deep learning-based ovarian tumor diagnosis (IEDL-OVD) model is

presented in [46]. The presented model seeks to improve the detection results by enhancing the quality of the input medical picture. An image enhancement method based on the BWO algorithm is included in the presented model. To identify the presence of the ovarian tumor, the VGG16 model is also used as a feature extractor and a stacked autoencoder (SAE) is used as a classifier.

A new technique for dehazing satellite photos called Adaptive Black Widow Optimization (ABWO) algorithm is suggested by Suresh et al. [117]. It was made by altering the transmission map utilized in the Dark Channel Prior (DCP) technique. The introduction of a Weighted Variance Guided Filter (WVGF), which incorporates a multiple-phase image decomposition and fusing procedure, is made to improve the image quality. The experimental findings show that the suggested method outperforms others, regardless of the haze intensity, while maintaining the natural appearance of the scene.

Additionally, Kaliswaran et al. [49] introduced BWO-ST, an effective BWO with a signcryption method for image steganography. Discrete Wavelet Transform (DWT) is used in the suggested model. Additionally, the BWO method is used for the best pixel selection procedure, and the encryption approach is used for encryption. Additionally, the chosen pixel position of the cover picture was receiving the encrypted image by embedding it there. The outcomes demonstrated the superiority of the BWO-ST method over other approaches.

## 5.9 Medical

A combination of the ACO, BWO, and CNN (ACO-BWO-CNN) approaches was offered by Kiruthika et al. [55] to diagnose Parkinson's disease in its early stages utilizing aspects of speech signals. The proposed method consists of three major parts, pre-processing, feature selection, and classification. The proposed method's learning rate is optimized using the BWO. The primary objective was to increase the model's effectiveness and accuracy while simultaneously lowering the computational cost of the classification task. Evaluations of the classification systems' accuracy with and without feature selection revealed a significant impact of feature selection. Results indicate that utilizing the feature selection method improves accuracy over not using it.

Raju et al. [89] introduced a combining approach of the Fuzzy Set (FS) algorithm, SVM, and BWO (FS-SVM-BWO) for skin disease detection. Five different kinds of skin disease images were used to evaluate the proposed approach. The Fuzzy set algorithm was applied in the segmentation phase, and the SVM-BWO algorithms were applied in the classification stage. BWO was utilized to enhance the classification performance of the SVM. The

**Table 2** Summary of the BWO's applications

Application	Abbreviation	Description	Area	Ref.
Feature selection	HSAA	Utilizing BWO to achieve better accuracy and scalability	Sentiment analysis	[22]
	BWOA	Integrating BWOA with K-means algorithm	Data Clustering	[69]
	MOBBWO	Using Multi-objective Opposition-based Binary BWO	Texts psychology	[38]
	SDABWO	Using Black Widow Optimization Algorithm	Feature selection	[42]
	NBWMHO	Introducing novel black widow (NBW) deep learning (DL)	Feature selection	[31]
	WFS	Using BWO to enhance the classification of data	Feature selection	[25]
Cloud computing	CBWOA	Using Chaotic BWO as a protocol to find a good routing	Routing protocol	[128]
	EEBWOSA	Using BWO to design energy-efficient scheduling solution	Task scheduling	[60]
	NBWO	Enhancing BWO to produce efficient and stable algorithm to solve discontinuity problems in the cloud environment	Task scheduling	[70]
	BWCSO	Combined BWO and Seagull Optimization to achieve optimal results	Cloud environments	[119]
IoT	HSRLBA	Employing the Black Widow Algorithm for Reinforcement Learning	Cloud computing	[48]
	IoT-ACDS	Integrating BWO with the IoT-ACDS to obtain precise and safe operation control of self-driving cars	Autonomous car driver scheme (ACDS)	[105]
	IBWO	Using BWO to optimize the cloud broker	Optimized cloud services broker	[92]
	LOADng-BWO	Using BWO to select the optimal parameters of the routing protocol	Routing protocol for IoT	[44]
	HSBWSO-RSP	Hybrid Sine-Cosine Black Widow Spider Optimization Route Selection Protocol	IoT-supported WSN	[11]
	LOADng-BWO	Optimizing LOADng parameters via the BWO algorithm tailored for IoT	Routing protocol	[105]
	FEBWS-SERPPA	Improved the BWO technique by ensuring the best cluster head selection within each cluster	IoT clusters	[100]
Cyber security	BWO-CONV-LSTM	Using BWO for hyper-parameter tuning of the CONV-LSTM	IDS	[50]
	BWO-RNN	Using BWO for feature selection and RNN for classification	Anomaly identification	[104]
Engineering	BWDBN	Using BWO with lean approach for reducing cycle time	Industrial Engineering	[120]
	IBWBSA	Using hybrid BWO and BSS algorithms	Energy engineering	[57]
	ASOCMA	Using BWO and Simulation	Electrical energy	[12]
	ODFDNLMW-1	Using BWO algorithm and Class-Shape Transformation	Electrical Engineering	[13]
	ODFDNLMW-2	Using BWO, Optimization-Pattern Search (SOPS), and GA	Electrical Engineering	[13]
	FCWM	Adaptive BWO and field waveform of the short-circuit test	Electrical Engineering	[67]
	SALBWO	Using Self Adaptive Levy Flight-based BWO (SALBWO)	Energy engineering	[32]
	SBWOA	Using Sobol sequence initialized BWO algorithm (SBWOA)	Electrical Engineering	[132]
	OADGDS	Using Black widow optimization algorithm (BWOA)	Energy engineering	[98]
	FOPID	Using meta-heuristic Black Widow Optimization (BWO)	Energy engineering	[72]

**Table 2** (continued)

Application	Abbreviation	Description	Area	Ref.
Power and energy	pv-BWO	A new metaheuristic pv-BWO algorithm is used to approximate the SDM, DDM, and TDM of solar PV	Electrical energy	[20]
	BWOA	A PID controller that has been tuned using BWOA for frequency management of an interconnected power system that includes thermal reheat and solar panel systems	Electrical power system	[21]
	MPPT technique	A novel MPPT control method based on the BWO is presented for partial shading conditions	Power generation system	[27]
	pv-BWO and cn-BWO	To estimate the parameters which equal to SDM and DDM, two innovative metaheuristic methods are used	Electrical energy	[19]
	BWO-DG	The position and capacity of numerous DGs are established and optimize using BWO	Distribution lines	[95]
	BWO	The proposed system method of proceeding maximizes economic revenue annually effectively	Distribution systems	[64]
	BWO	BWO uses sample day load data and an annualized model to determine the ideal HES size	Hybrid energy system	[116]
Networks	TC-MBWO	Using BWO for securing data transmission in WSN	Routing protocol for WSN	[18]
	EBWO	Using BWO to select the optimal number sensors in WSN	Sensor deployment	[23]
	BWOA	Using BWO to detect the sensor vertices superior compromise potential by attack	Node capture attack	[54]
	BWO-BOA	Using a hybrid optimization model to reduce the dimension of features in network intrusion detection	Feature selection	[111]

proposed approach was evaluated on ISIC-2018 datasets, and the experimental results were compared to five algorithms, including GA, FBWO, PSO, ACO, and ABC. Compared to competitive algorithms, the proposed approach showed superior performance.

To test sample data from the Chinese hamster ovary (CHO), Munirah et al. [74] used BWO to analyze the sample data from CHO. The proposed algorithm was compared with the PSO, DE, and BOA algorithms. The BWO was employed to avoid traps in local optima and enhance the exploration process. The simulation results showed that, despite taking a lot of time to perform, the proposed approach produced better results in terms of solution cost.

Ramya and Lakshmi [90] combined a Fractional BWO with NN (FBW-NN) for early symptoms detection of Acute Myelogenous Leukemia (AML). The FBW technique was used to enhance the efficiency of NN in terms of hidden layer parameters and weights. The Munich AML Morphology dataset and CPTAC-AML datasets were used to evaluate the proposed algorithm. Results showed that the FBW-NN provides better convergence performance than BWO, ABC, TSA, and PSO. Additionally, superior AML detection results were obtained in comparison CNN, Naive Bayes, SVM, chronological sine cosine-based actor-critic NN, and pre-trained deep CNN.

## 5.10 Nature

A meta-heuristic method has been devised to tackle multi-objective optimization issues in hazardous materials and waste management [87]. The algorithm is known as multi-objective MOBWO. The MOBWO uses a novel Minkowski-based strategy to select a single solution from a set of non-dominated first-front alternatives as the final optimum solution. The MOBWO attempts to decrease supply chain risk, transportation costs, and greenhouse gas emissions. The MOBWO algorithm performs better in large-scale test issues than in small- and medium-scale test problems.

Mathur et al. [65] proposed the Riverol-Pilipovik (RP) water treatment facility, a proportional integral derivative (PID) controller based on the BWO method is suggested. A decoupler is used to transform the two interacting loops in the plant's two-input, two-output (TITO) system into non-interacting loops. By calculating an integral square error (ISE) and minimizing it, PID controllers are created. The ISE is minimized in this work using the BWO algorithm. The interval model of the RP water treatment plant is taken into account, and the controller is constructed utilizing the BWO and Jaya algorithms for both the lower interval and upper interval models. The outcomes support the suggested BWO-based PID controller's accuracy. The controller design is also effective and reliable.

**Table 3** Cont. summary of the BWO's applications

Application	Abbreviation	Description	Area	References
Image processing	EBWO	Employing BWO to identify the ideal multilevel thresholding setting of fitness functions for a grayscale image	Image Processing, Multilevel thresholding	[88]
	BWO-based method	Employing BWO to identify the idea multilevel thresholding of fitness functions tested on brain tumors	Image Processing, Multilevel thresholding	[39]
	BWO	Employing BWO to identify the idea multilevel thresholding of fitness functions for a grayscale and color images	Image Processing, Multilevel thresholding	[4]
	IEDL-OVD	Intelligent Image Enhancement with a deep learning-based ovarian tumor diagnosis model	Image Processing, tumor diagnosis	[45]
	ABWO	A new technique for dehazing satellite images	De-hazing images	[46]
	BWO-ST	Combines BWO with signcryption method for image steganography	Image steganography	[110]
Medical	ACO-BWO-CNN	Used to diagnose Parkinson's disease (PD) in its early stages	Feature selection	[55]
	FS-SVM-BWO	Used to identify skin diseases	Image processing	[89]
	BWO	Employed BWO to analyze sample data from Chinese Hamster Ovary	Parameter estimation	[74]
	FBW-NN	FBW-NN is employed for early symptoms detection of Acute Myelogenous Leukemia	Feature extraction	[90]
Nature	MOBWO	MOBWO uses a Minkowski-based strategy to select a single solution as the final optimum solution	Greenhouse gas emissions	[87]
	BWO-based PID controller	A decoupler is used to transform the two interacting loops in the plant's TITO system into non-interacting loops	Water treatment plant	[65]
	ANFIS-BWO and SVR-BWO	A BWO algorithm was employed in conjunction with ANFIS and SVR	Seasonal wave height	[66]
	ANFIS-BWOA and SVM-BWOA	ANFIS-BWOA and SVM-BWOA were used to estimate SSL	Water engineering	[78]

The maximum seasonal wave height was predicted by authors in [66] using an integrated methodology (ANFIS-BWO and SVR-BWO). To research the impact of seasons on the maximum wave height, a buoy station was put in the southern Baltic Sea and collected wave data throughout the year. The wave data are made up of a time series with irregular spacing. The outcomes demonstrated that the BWO application improved ANFIS and SVR accuracy. Additionally, various runs showed that the BWO is stable enough to obtain the global solution. The outcomes also demonstrate the accuracy of SVR-BWO as a model.

In [78], the SLL of two major tributaries of the Telar River located in northern Iran was estimated using the adaptive neuro-fuzzy interface system (ANFIS) and support vector machine (SVM). The ANFIS and SVM models' daily SSL prediction accuracy was improved by BWOA. The inputs to the models were temperature, lagged rainfall, discharge, and SSL. To choose the ideal input scenario, the study developed a new hybrid Gamma test. Later, the optimal input combination was selected based on the

gamma value. Tables 2, 3 show a summary of the BWO's applications.

## 6 Evaluation and discussion

This section introduces two types of evaluations. First, the evaluation of the efficiency of the BWO comparing the other similar algorithms in the literature as shown in Table 4. Second, highlights the contributions of the proposed variants of BWO by the researchers as shown in Table 5.

The results of Table 4 showed that the BWO is different from the other algorithms in some attributes such as the number of variables and the complexity. On the other hand, it shares its properties with other algorithms in the strengths, weaknesses, and convergence rate. It is worth mentioning that the other algorithms were selected from different kinds of optimization algorithms. For instance, evolutionary algorithms, physics-based algorithms, and swarm-based algorithms. It can be noticed that the basic

**Table 4** Comparison between basic BWO and other algorithms

Properties	Algorithm					
	BWO	CAS	GA	PSO	HS	TS
Proposed	[36]	[127]	[37]	[53]	[29]	[30]
Parameter	Three	Three	Three	Five	Three	Four
Complexity	[129] $O(N \times (T + TD + 1))$	[110] $O(n.D.t_{max})$	[75] $O(m^2)$	[1] $O(nm^2)$	[16] $O(HMS \times M + HMS \times \log(HMS))$	[130] $O(mn^2)$
Convergence	[36] Smooth convergence with fast rate [26]	[97] Slow convergence rate [108]	[3] Fast convergence [124]	[113] Quickly converge [62]	[122] Suffer from premature convergence [33]	[94] Rapidly converged [130]
Strength	[86] Balance between exploration and exploitation	[77] Balance between intensification and diversification	[10] Deal with the complex fitness landscape	[6] Don't have overlapping and mutation calculation	[68] Increases the diversity of the new solutions	[59] Avoid trapped at local optimum
Weaknesses	Searching performance is conventional [131]	Trapped in a local optimum [112]	Evaluation is relatively expensive [134]	Suffers from partial optimism [9]	Get stuck on local optima [68]	Needs huge memory resources [59]

**Table 5** Comparisons between BWO's variants

Abbreviation	Improvements					Total of improvements	References
	Local optima	Convergence rate	Diversity	Balance between explor and exploit	Performance		
MBWO-PSO		✓	✓		✓	3/5	[17]
BWDERD	✓		✓	✓	✓	4/5	[123]
QIWBWO	✓	✓	✓		✓	4/5	[40]
ChBWO					✓	1/5	[73]
BWO-NMB	✓				✓	2/5	[43]
MBWO	✓	✓	✓	✓	✓	5/5	[103]
EBWO	✓	✓	✓	✓	✓	5/5	[28]
IBWOA	✓	✓	✓	✓	✓	5/5	[121]
LDBWO	✓	✓	✓	✓	✓	5/5	[41]
BMBWFL		✓			✓	2/5	[115]
HDRNN-MBWO					✓	1/5	[8]
BWFSO					✓	1/5	[63]
BWO-BOA	✓	✓			✓	3/5	[126]
IIT2FLS-HEED		✓			✓	2/5	[114]
BW-SMO		✓			✓	2/5	[85]
AHMBWO		✓	✓		✓	3/5	[93]
ANFIS-BWO		✓			✓	2/5	[66]
OBL-BWO, FOPID <sup>2</sup> FF <sup>2</sup>	✓	✓			✓	3/5	[82]



BWO need some improvements to increase its features and fix the weaknesses to outperform the rest of the algorithms.

Table 5 collected the tries of researchers to enhance the weaknesses of BWO by introducing new versions (i.e., the variants of basic BWO). These weaknesses are summarized into five points, such as getting stuck in local optima, slow convergence rate, losing the diversity of the agent search, unbalancing between the exploitation search mechanism and exploration search mechanism, and the performance. The results illustrate that most of the introduced versions focused on fixing the local search, convergence and diversity. Finally, there are some researchers used the strength of BWO to solve their problems (i.e., they used BWO as it without conducting any modifications) such as [24, 47, 81, 91, 133].

## 7 Conclusion and future works

This review paper includes around a hundred articles related to the BWO algorithm from 2020 until February 2023. The collected articles were classified into different fields. For instance, Economics, Energy and Power Flow, Engineering, and Medical. Furthermore, the rest of these articles were classified based on the variants of BWO. For instance, Binary, Discrete, Multi-objectives, Modification, and Hybridization. These articles were reviewed to extract the strengths, weaknesses, and features of BWO. So, this review paper enables us to lead and guide interested students and researchers in different fields, such as providing solutions for pilgrim crowds to complete their rituals, easily.

The BWO proposed recently compared with other metaheuristic algorithms. It is a promising algorithm because it proves its effectiveness in dealing with various problems in various fields. The BWO's merits helped in its success. For example, it has a search mechanism for looking at the local optima and a search mechanism for looking at the global optima using the features of population-based methods and gradient-based methods. In contrast, the local search mechanism may lead to getting stuck in a bad local optimum [34]. Also, it suffers from a weakness in dealing with large-domain problems which leads to raised computational time [84].

Although the BWO has advantages like other optimization algorithms, such as simplicity, fewer parameters, and the ability to hybridize with other algorithms, easily. But, BWO shortage the mathematical analysis. In other words, BWO does not have a theoretical analysis like GA [125] and PSO [101]. Therefore, the researchers solved this issue using the features of other optimization algorithms by hybridizing BWO.

Finally, this paragraph presents suggestions and possible future directions in the hope of being useful for interested researchers. First, common selection schemes (Tournament Selection, Proportional Selection, and Linear Rank Selection) can be included to enhance the quality of the selected solutions [107]. Second, it can take advantage of the local search algorithms ( Hill-climbing and Simulating Annealing) to avoid the rapid convergence which leads to avoiding being stuck in local optimum [109, 111].

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## Declarations

**Conflict of interest** The authors declare that they have no conflicts of interest.

**Ethical approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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