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SURVEY ARTICLE

Recent Developments in Equilibrium Optimizer Algorithm: Its Variants and Applications

Rebika Rai[1] · Krishna Gopal Dhal[2]

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Abstract

There have been many algorithms created and introduced in the literature inspired by various events observable in nature, such as evolutionary phenomena, the actions of social creatures or agents, broad principles based on physical processes, the nature of chemical reactions, human behavior, superiority, and intelligence, intelligent behavior of plants, numerical techniques and mathematics programming procedure and its orientation. Nature-inspired metaheuristic algorithms have dominated the scientific literature and have become a widely used computing paradigm over the past two decades. Equilibrium Optimizer, popularly known as EO, is a population-based, nature-inspired meta-heuristics that belongs to the class of Physics based optimization algorithms, enthused by dynamic source and sink models with a physics foundation that are used to make educated guesses about equilibrium states. EO has achieved massive recognition, and there are quite a few changes made to existing EOs. This article gives a thorough review of EO and its variations. We started with 175 research articles published by several major publishers. Additionally, we discuss the strengths and weaknesses of the algorithms to help researchers find the variant that best suits their needs. The core optimization problems from numerous application areas using EO are also covered in the study, including image classification, scheduling problems, and many others. Lastly, this work recommends a few potential areas for EO research in the future.

1 Introduction

Finding the ideal configuration of a set of decision variables to reduce or exploit precise measures, along with constraints and parameters, articulated in the objective function [1] is typically the focus of Optimization. The optimization procedure with the fundamental objective function explores a search space in which the optimal solution to a particular problem must be identified. The zone of optimization by means of meta-heuristics has gained massive acceptance with swelling curiosity from researchers from diverse arenas, which is the reason why quite a lot of meta-heuristics are being anticipated recurrently as a solution to composite and real-world problems. A metaheuristic algorithm, or population-based method as it is more frequently called, offers a universal optimization basis that is effortlessly adaptable to a wide range of optimization problems, thereby discovering and manipulating the search space through the use of operators and performing operations, namely parameter tuning and modification. Population-based nature-inspired metaheuristic are essentially categorized in numerous ways (6 categories or classes) based on the inspiration, such as "swarm-inspired", "chemistry-inspired", "human-inspired", "plant-inspired", "maths-inspired" and "physics-inspired", and the same has been projected in Table 1 along with a few of the algorithms under each category.

Swarm-Inspired metaheuristics are the first class of population-based nature-inspired metaheuristics, wherein swarms imitate actions of social animals available in nature such as foraging behavior of ants, flocking behavior of birds, schooling of fish, moulding behavior of bacteria, herding behavior of animals, and many more. The following are a few of the swarm-inspired algorithms listed, Ant Colony Optimization [2], Cuckoo Search [3], Artificial Bee Colony Algorithm [4], Particle Swarm Optimization [5], Firefly Algorithm [6], Krill Herd Algorithm [7], Bat Algorithm

✉ Rebika Rai
rrai@cus.ac.in

Krishna Gopal Dhal
krishnagopal.dhal@midnaporecollege.ac.in

1 Department of Computer Applications, Sikkim University, Sikkim, India

2 Department of Computer Science and Application, Midnapore College (Autonomous), Paschim Medinipur, Midnapore, West Bengal, India

Table 1 Classification of population-based nature-inspired meta-heuristic algorithms

Population-based nature-inspired meta-heuristic algorithms					
Swarm-inspired	Physics-inspired	Chemistry-inspired	Human-inspired	Plant-inspired	Math-inspired
Ant Colony Optimization (ACO)	Equilibrium Optimizer (EO)	Chemical Reaction Optimization (CRO)	Brain Storm Optimization (BSO)	Plant Growth Optimization (PGO)	Hyper-Spherical Search Algorithm (HSS)
Cuckoo Search (CS)	Multi-Verse Optimization (MVO)	Henry Gas Solubility Optimization (HGSO)	Teaching Learning-Based Optimization (TLBO)	Photosynthetic Algorithm (PA)	Radial Movement Optimization (RMO)
Artificial Bee Colony Algorithm (ABC)	Big Bang-Big Crunch Algorithm (BBBC)	Artificial Chemical Reaction Optimization (ACRO)	Class Topper Optimization (CTO)	Plant Propagation Algorithm (PPA)	Stochastic Fractal Search (SFA)
Particle Swarm Optimization (PSO)	Magnetic Charged System Search (MCSS)		Imperialist Competitive Algorithm (ICA)	Artificial Root Foraging Algorithm (ARFA)	Golden Ratio Optimization Method (GROM)
Firefly Algorithm (FA)	Central Force Optimization (CFO)		Human Mental Search (HMS)	Paddy Field Algorithm (PFA)	Sine Cosine Algorithm (SCA)
Kill Herd Algorithm (KHA)	Thermal Exchange Optimization (TEO)		Search and Rescue Optimization (SRO)	Root Mass Optimization Algorithm (RMO)	Arithmetic Optimization Algorithm (AOA)
Bat Algorithm (BA)	Ray Optimization (RO)		Election Algorithm (EA)	Fertile Field Algorithm (FFA)	
Manta Ray Foraging Optimization (MRFO)	Gravitational Local Search Optimization (GLSO)		Gaining Sharing Knowledge-Based Algorithm (GSK)	Flower Pollination Algorithm (FPA)	
Moth-Flame Optimization Algorithm (MFO)	Artificial Physicomimetics Optimization (APO)		Forensic-Based Investigation Optimization (FBIO)	Path Planning inspired by Plant Growth (PGPP)	
Dragonfly Algorithm (DA)	Optics Inspired Optimization (OIO)		Football Game Algorithm (FGA)	Invasive Weed Optimization (IWO)	
Marine Predators Algorithm (MPA)	Electromagnetic Field Optimization (EFO)		Life Choice-Based Optimization (LCBO)	Rooted Tree Optimization (RTO)	
Whale Optimization Algorithm (WOA)	Gravitational Local Search Optimization (GLSO)		Corona virus Herd Immunity Optimization (CHIO)	Sapling Growing up Algorithm (SGA)	
Whale Optimization Algorithm (WOA)	Electromagnetism-like Algorithm (EM)		Battle Royale Optimization (BRO)	Root Growth Algorithm (RGA)	

[8], Manta Ray Foraging Optimization [9], Moth-Flame Optimization Algorithm [10], Dragonfly Algorithm [11], Marine Predators Algorithm [12], Gray Wolf Optimization [13] and Whale Optimization Algorithm [14]. The second class of Population-based Nature-inspired metaheuristic is *Chemistry-Inspired* where the nature of chemical processes serves as the primary foundation of inspiration for developing answers to challenges that arise in the present. Some of the algorithms under this category are Chemical Reaction Optimization [15], Henry Gas Solubility Optimization [16], and Artificial Chemical Reaction Optimization [17].

As highlighted in Table 1, a third class of population-based, nature-inspired metaheuristics is *Human-Inspired* that impersonate human behavior, dominance, and intelligence. The following is a list of some of the human-based algorithms shown in Table 1 i.e., Brain Storm Optimization [18], Teaching Learning-Based Optimization [19], Class Topper Optimization [20], Imperialist Competitive Algorithm [21], Human Mental Search [22], Search and Rescue Optimization [23], Election Algorithm [24], Gaining Sharing Knowledge-Based Algorithm [25], Forensic-Based Investigation Optimization [26], Football Game Algorithm [27], Life Choice-Based Optimization [28], Corona virus Herd Immunity Optimization [29] and Battle Royale Optimization [30]. The fifth class of metaheuristics, called *Plant-Inspired* population-based nature-inspired metaheuristics, essentially imitates the intelligent behavior displayed by plants. Some of the well-known plant-based algorithms include the ones listed below: Plant Growth Optimization [31], Photosynthetic Algorithm [32], Plant Propagation Algorithm [33], Artificial Plant Optimization Algorithm [34], Paddy Field Algorithm [35], Root Mass Optimization Algorithm [36], Fertile Field Algorithm [37], Flower Pollination Algorithm [38], Path Planning inspired by Plant Growth [39], Invasive Weed Optimization [40], Rooted Tree Optimization [41], Sapling Growing up Algorithm [42] and Root Growth Algorithm [43]. The *Math-Inspired* is sixth category under population-based, nature-inspired meta-heuristic optimization, which essentially tends to mimic the method of numerical techniques, mathematical programming, and its focus on resolving a variety of constraints and optimization problems in the real world. Several well-known math-inspired algorithms include Hyper-Spherical Search Algorithm [44], Radial Movement Optimization [45], Stochastic Fractal Search [46], Golden Ratio Optimization Method [47], Sine Cosine Algorithm [48] [49] and Arithmetic Optimization Algorithm [50]. Finally, the last class of Population-based Nature-inspired meta-heuristic optimization portrayed in Fig. 1 is *Physics-Inspired* in which the main source of inspiration is the physical processes, which are further formulated into solutions to resolve the problems. A few popular physics-inspired algorithms are: Equilibrium Optimizer [51], Multi-Verse Optimization [52], Bang-Big Big-Crunch Algorithm [53], Magnetic Charged System Search [54], Central Force Optimization [55], Thermal Exchange Optimization [56], Ray Optimization [57], Gravitational Search Algorithm [58], Artificial Physicomimetics Optimization [59], Optics Inspired Optimization [60], Electromagnetic Field Optimization [61], Gravitational Local Search Optimization [62] and Electromagnetism-like Algorithm [63]. As already mentioned, all these classes of algorithms are enthused by nature and its natural phenomena, and are both robust and flexible to adapt across scenarios and problems.

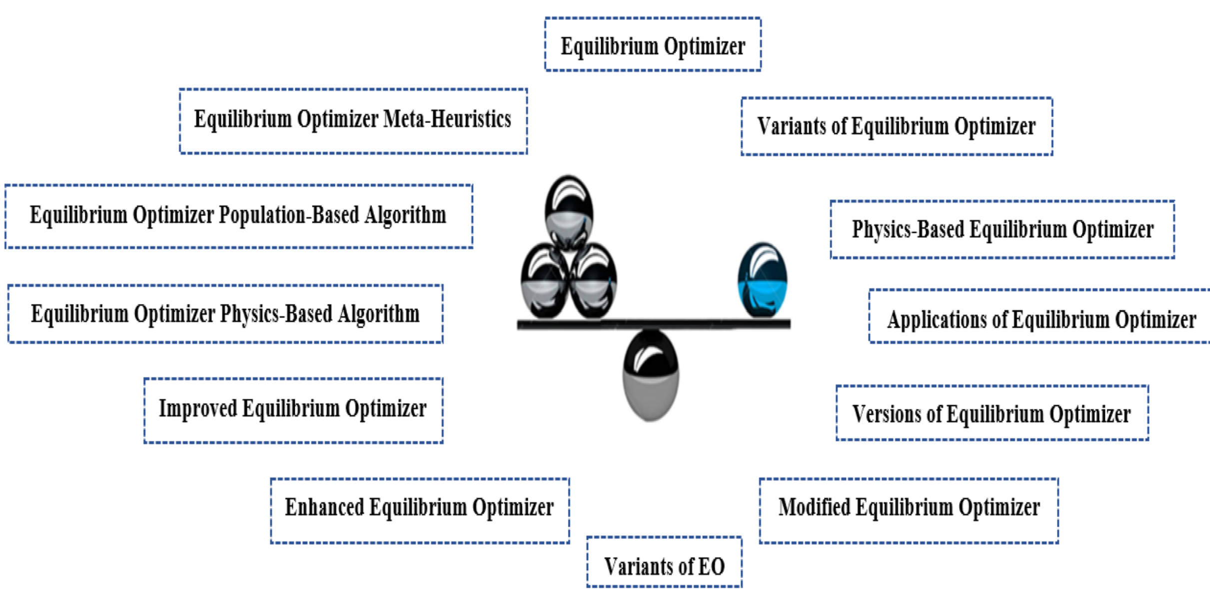


Fig. 1 Terminologies used for searching EO research papers from Google Scholar

Equilibrium Optimizer (EO) [51], is an example of a predominant physics-inspired population-based nature-inspired meta-heuristic optimization algorithms announced in the year 2020 by Afshin Faramarzi and group [51] that basically mimic the dynamic mass balance on a control volume. EO has seen a sharp increase in popularity in recent years, reaching 1842 total citations according to the survey performed on Google Scholar on February 5, 2023. Several EO's variants have been developed by the researchers and used for various optimization problems, for instance, feature selection, photovoltaic models, medical data and image classification, image segmentation, scheduling, sentiment analysis, technical problems, and so on discussed and summarized in the subsequent section. To the best of our knowledge, no review or survey paper on EO has been published as of yet, and this is the main impetus behind this work. The purpose of this paper is therefore to present a thorough and understandable description of the pertinent work related to EO and its variations, as well as the proposed applications for further investigation of EO in order to fix various problems and find optimal solutions for the realm. This article further discusses the strengths and weaknesses of the aforementioned algorithms. This will undoubtedly help interested researchers and students in choosing the best option to address the issue at hand. In this review paper, all work related to the Equilibrium Optimizer (EO) will be rigorously examined, addressing five pillars:

- The evolution of EO-related articles in the literature related to amount of citations, publications, year of development, top 10 publishers, and top 10 journals is depicted in Sect. 2.
- The basic concept of EO is highlighted in terms of inspiration, mathematical model, original algorithm, procedural steps, and flowcharts in Sect. 3. Along with the other details, a summary of the various research works carried out using the basic EO and original EO is highlighted.
- An in-depth literature review of basic EO and its variants (Revised and Hybridized) is discussed in Sect. 4.
- All applications tackled by EO and its variants are also illustrated in Sect. 5.
- Finally, this paper concludes and endorses some of the possible future research directions for EO, which is available in Sect. 6.

2 The Evolution of Equilibrium Optimizer Algorithm in the Literature

No one algorithm can produce the best solutions for all optimization problems, or for all instances of the same issue, as the No Free Lunch (NFL) theorem correctly states. Hence, the basic form of any nature-inspired meta-heuristic algorithm can be revised or even hybridized in order to meet the requirement. Thus, numerous problem-dependent variants of EO have been proposed since 2020 to enhance not just its searching behavior, but also to generate the optimal solutions to the problem at hand. This section provides an overview of how EO has been used in academic articles to evaluate the evolution of EO in the literature. Numerous publications from leading publishers such as IEEE, Elsevier, Springer, MDPI, AIMS Press, Nature Portfolio, Taylor & Francis, Wiley and Hindawi were considered. To do this, the web search engines listed below are used, which offer the full text of academic literature across a variety of publication disciplines and search is conducted using some of the terms shown in Fig. 1 (albeit not exclusively).

(a) Google Scholar (https://scholar.google.com),
(b) IEEE Xplore (https://ieeexplore.ieee.org),
(c) ScienceDirect (https://www.sciencedirect.com),
(d) SpringerLink (https://www.springerlink.com),
(e) ACM Digital Library (https://dl.acm.org) and
(f) DBLP (https://dblp.uni-trier.de)

Furthermore, to scrutinize the huge number of research papers found in the web search engines, a few enclosure and omission norms were well-thought-out and used, as listed below:

Enclosure norms	Omission norms
Papers published in authentic journals/conferences	Predatory publication at conferences and journals
English language research papers	Papers written in languages other than English
If full papers are available for download	If the full paper cannot be downloaded

After utilizing the enclosure and omission norms, a collection of 175 research papers (3 papers are pre-print versions) related to EO, published in different conferences and journals, has been finalized as depicted in Fig. 2. Year-wise publications of the above-mentioned 175 EO related research papers are depicted in Fig. 3. Researchers from numerous domains considered EO to be the leading algorithm in the years mentioned, and this is also reflected in their publications. In 2020, when EO was first introduced, the number of EO-based publications was twenty, grew to 68 by the end of 2021, reaching 80 publications in 2022. EO gained much attention from the research community, leading to seven new publications in the first few months of 2023. As per the survey, as mentioned earlier, over the past few years (2020 till date), EO has received a total of 1842 citations according to Google Scholar and in this context, the year-wise citations for the different

Fig. 2 Different EO related papers published in different journals and conferences (As per the survey)

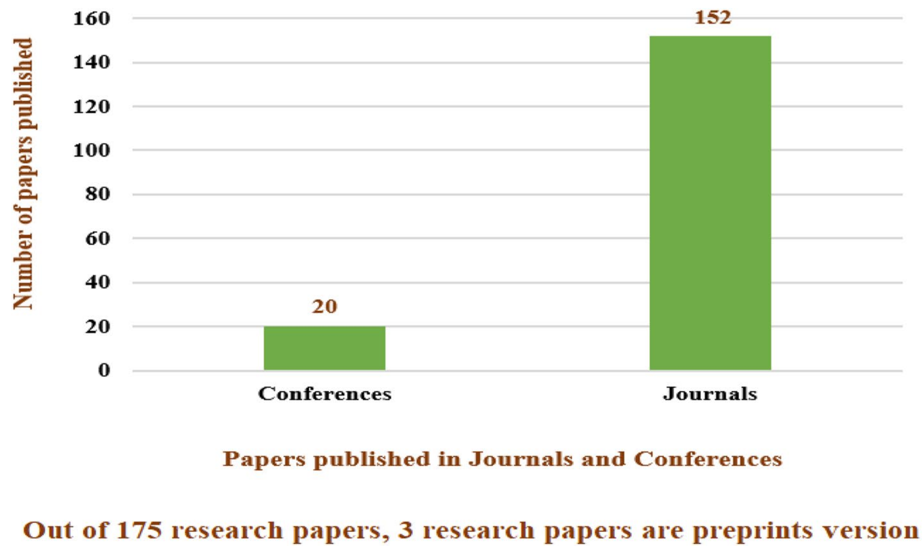


Fig. 3 Year-wise EO related research papers published (As per the survey)

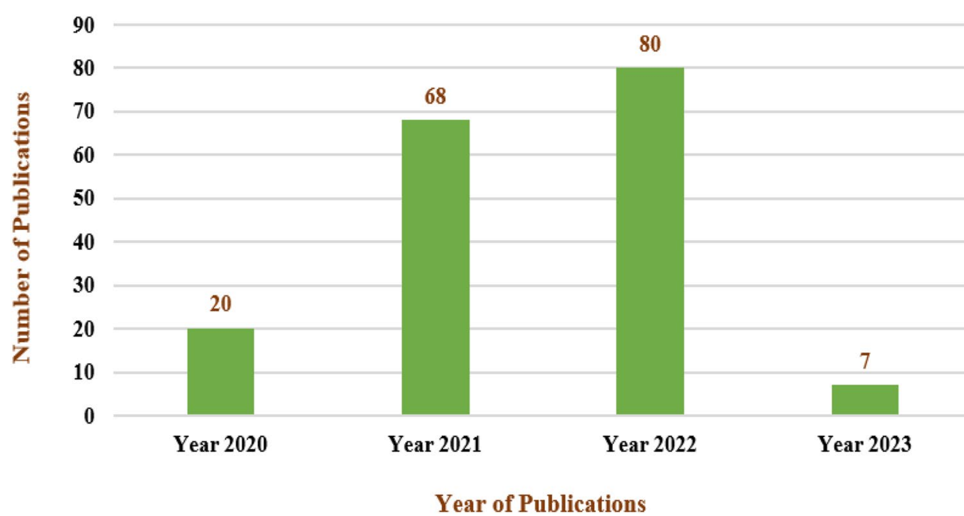
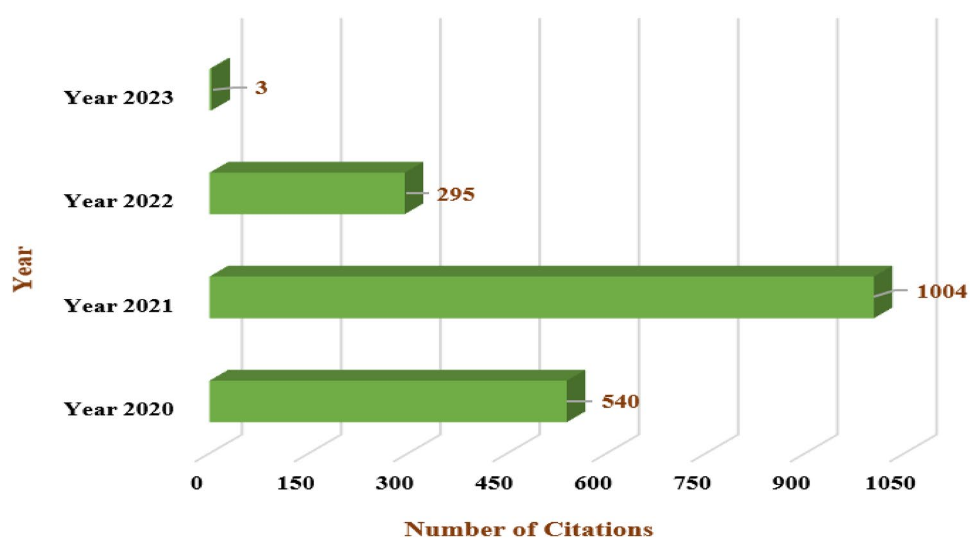


Fig. 4 Year-wise citations for the EO related research papers published (As per the survey)



EO-related papers are highlighted in Fig. 4. Furthermore, as shown in Fig. 5, EO-related articles are published in reputable journals and conferences by well-established publishers, which depicts various EO-related articles published by the top 10 publishers, namely, Elsevier, IEEE, Springer, MDPI, Hindawi, Wiley, Taylor & Francis, Taiwan Ubiquitous Information, World Scientific, and Plos as per the survey. Last but not least, Fig. 6 lists the top 10 journals for EO-related article publishing.

3 Equilibrium Optimizer Algorithm: An Overview

In this section, an overview of Equilibrium Optimizer (EO) is presented that mostly focuses on the inspirational source, mathematical model, original algorithm, and procedural steps of EO. The Equilibrium Optimizer (EO) algorithm is the population-based nature-inspired physics-based meta-heuristic optimization algorithms introduced in 2020 by Afshin Faramarzi

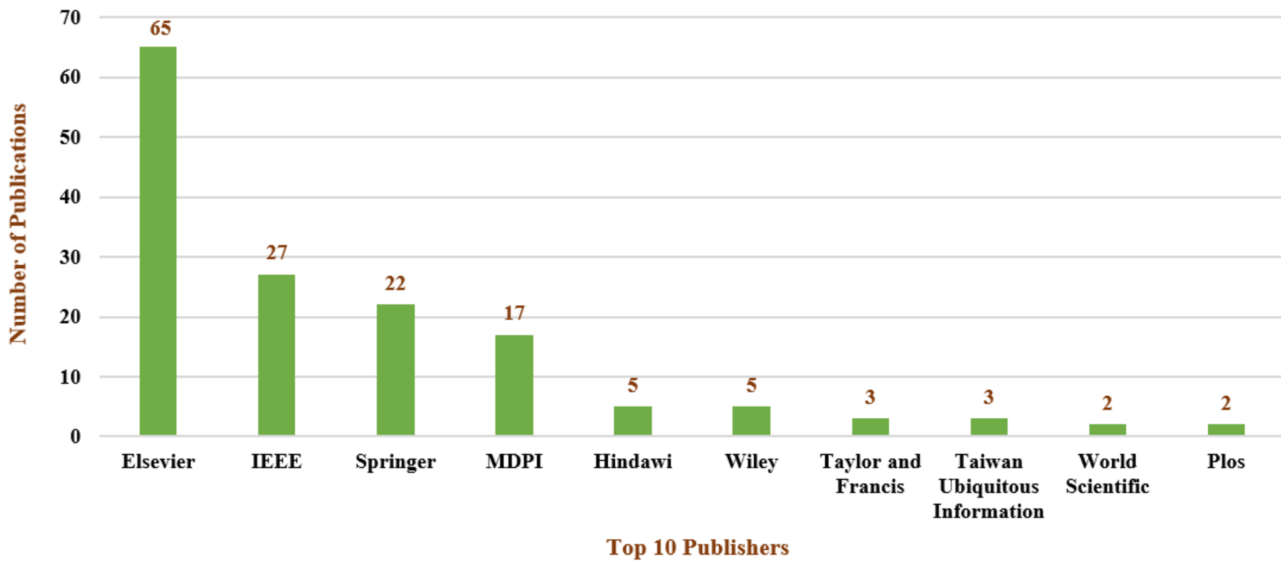


Fig. 5 Top 10 publishers publishing the EO-related research papers (As per the survey)

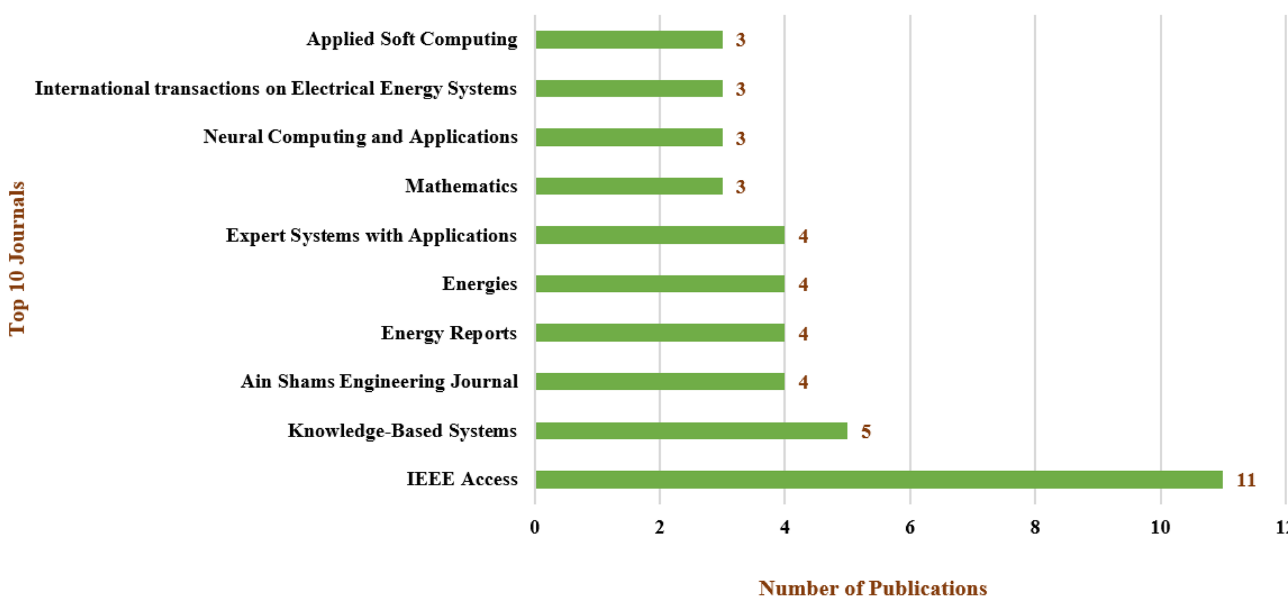


Fig. 6 Top 10 journals publishing the EO-related research papers (As per the survey)

and his group [51] that mimics the simple dynamic mass balance on a control volume. Equations related to mass balance of EO provide a physical basis for conserving the arrived, departed, and generated masses in control volumes.EO starts the optimization process by creating an initial population, just like other metaheuristic algorithms. Similar to the PSO method, in EO, particles correspond to solutions and concentrations correspond to particle positions.

Few important terminologies are intensive in EO in regard to the updating rules of the particles and positions of particles namely, Equilibrium concentration, Equilibrium pool, Exponential term and Generation rate. Also defined below are the means by which each term influences the search pattern. Equation 1 illustrates how the starting population is made up of the quantity of particles with the least and maximum dimension given a uniform random initialization in the search space.

$$C_i^{initial} = C_{min} + rand_i\left(C_{max} - C_{min}\right) \;\; i = 1, 2 \ldots .N \tag{1}$$

Here, $C_i^{initial}$ represents the initial concentration vector of the *i-th* particle; N is the number of particles; C indicates the position of the particle; $C_{max} and C_{min}$ are the maximum and minimum values for the dimensions; *rand* is a random vector with value between 0 and 1.

Once the initial population generation is complete, the EO algorithm proceeds to the next step. There, particles are evaluated using a fitness function and permuted to identify equilibrium candidates. Although knowledge of the equilibrium state is unknown in the early stages of the optimization process, equilibrium candidates must be identified in order to determine particle's search pattern, and the identified suitable candidates are kept in the equilibrium pool. By identifying the full optimization process, 4 best performing particles to date from the pool are selected and used in order to update.

The selected candidates help explore the unexplored search space, enhancing EO's ability to achieve better searches. Further, averaging these candidates enhances the ability to exploit EO to achieve global optima. With this concept in mind, the Equilibrium vector pool wherein the promising candidates are stored during the entire process is constructed as shown in Eqs. 2 and 3. The particle placements are updated based on a random pick among the five candidates available from the pool at each iteration until the optimization process is complete.

$$C_{eq.pool} = \left\{C_{eq(1)}, C_{eq(2)}, C_{eq(3)}, C_{eq(4)}, C_{eq(ave)}\right\} \tag{2}$$

$$C_{eq(ave)} = \frac{C_{eq(1)} + C_{eq(2)} + C_{eq(3)} + C_{eq(4)}}{4} \tag{3}$$

Here, $C_{eq.pool}$ is the Equilibrium pool; $C_{eq(1)}, C_{eq(2)}, C_{eq(3)}, C_{eq(4)}$ are the four best-so-far candidates chosen for the pool; $C_{eq(ave)}$ is the average of the four best-so-far candidates.

To maintain adequate stability between global and local searches in the search space, or between exploration and exploitation, exponential terms that primarily contribute to the update process needs to be evaluated, as shown in Eq. 4.

$$F = \exp\left(-\lambda\left(t - t_0\right)\right) \tag{4}$$

Here, F denotes the Exponential term; λ is the random vector [1]; and t is the time and the same is computed as shown in Eq. 5.

$$t = \left(1 - \frac{Iter}{MaxIter}\right)^{\left(\alpha \frac{Iter}{MaxIter}\right)} \tag{5}$$

Here, *Iter* refers to current iteration; *MaxIter* denotes the maximum number of iterations; α is a constant basically employed to regulate the behavior of the local search mechanism and t_0 denotes the parameter used to carry out exploration and exploitation as shown in Eq. 6.

$$t_0 = \frac{1}{\lambda}\mathrm{In}\left(-\beta sign(r - 0.5)\left[1 - \exp\left(-\lambda\right)\right]\right) - 1 \tag{6}$$

Further, Eq. 7 is the revised variant of Eq. 4 along with the substitution of Eq. 6 in Eq. 4.

$$F = \beta sign(r - 0.5)\left[\exp\left(-\lambda t\right) - 1\right. \tag{7}$$

Here, r is a random vector [0,1]; β refers to the constant for handling the exploration ability; α and β are assigned values 1 and 2 respectively as per [51]; sign (r − 0.5) is employed to advance the direction of exploration and exploitation.

The generation rate needs to be expressed as stated in Eq. 7 in order to further explore the search spaces and enhance the exploitation phase to deliver the precise response to the problem.

$$G = G_0 \exp\left(-\lambda\left(t - t_0\right)\right) = G_0 F \tag{8}$$

$$G_0 = GCP\left(C_{eq} - \lambda X\right) \tag{9}$$

$$GCP = \begin{cases} 0.5, & r_1, r_2 \geq GP \\ 0, & r_2 < GP \end{cases} \tag{10}$$

Here, G denotes the Generate rate; C_{eq} denotes the random candidate chosen from the Equilibrium pool; r_1 and r_2 are random vectors [0,1]; G_0 refers to the initial value and is generated using Eq. 8; GCP refers to the Generation rate Control Parameter evaluated using Eq. 9 and GP signifies the Generation Probability.

Finally, the rule for updating in EO is defined using Eq. 10, wherein F refers to the exponential term; G denotes the Generate rate; V denotes a constant initialized with a value 1 as per [2]; C denotes the position of the particle; and

C_{eq} represents a random candidate chosen from the Equilibrium pool.

$$C = C_{eq} + \left(C - C_{eq}\right)F + \frac{G}{\lambda V}(1 - F) \tag{11}$$

Incorporating the particle's memory saving mechanism that benefits the algorithm's exploitation capacity would undoubtedly improve its performance, so it's worth noting that the EO algorithm does so. The procedural steps of EO is portrayed in Fig. 7, and its pseudocode [51] is presented in Algorithm 1. Lastly, the summary of the different research works carried out by different researchers using the basic or original EO to resolve different problems belonging to numerous applications areas is discussed and tabulated in Table 2.

Finally, Table 2 discusses and tabulates the different research works conducted by various researchers using the basic or original EO to solve various problems in a variety of application areas.

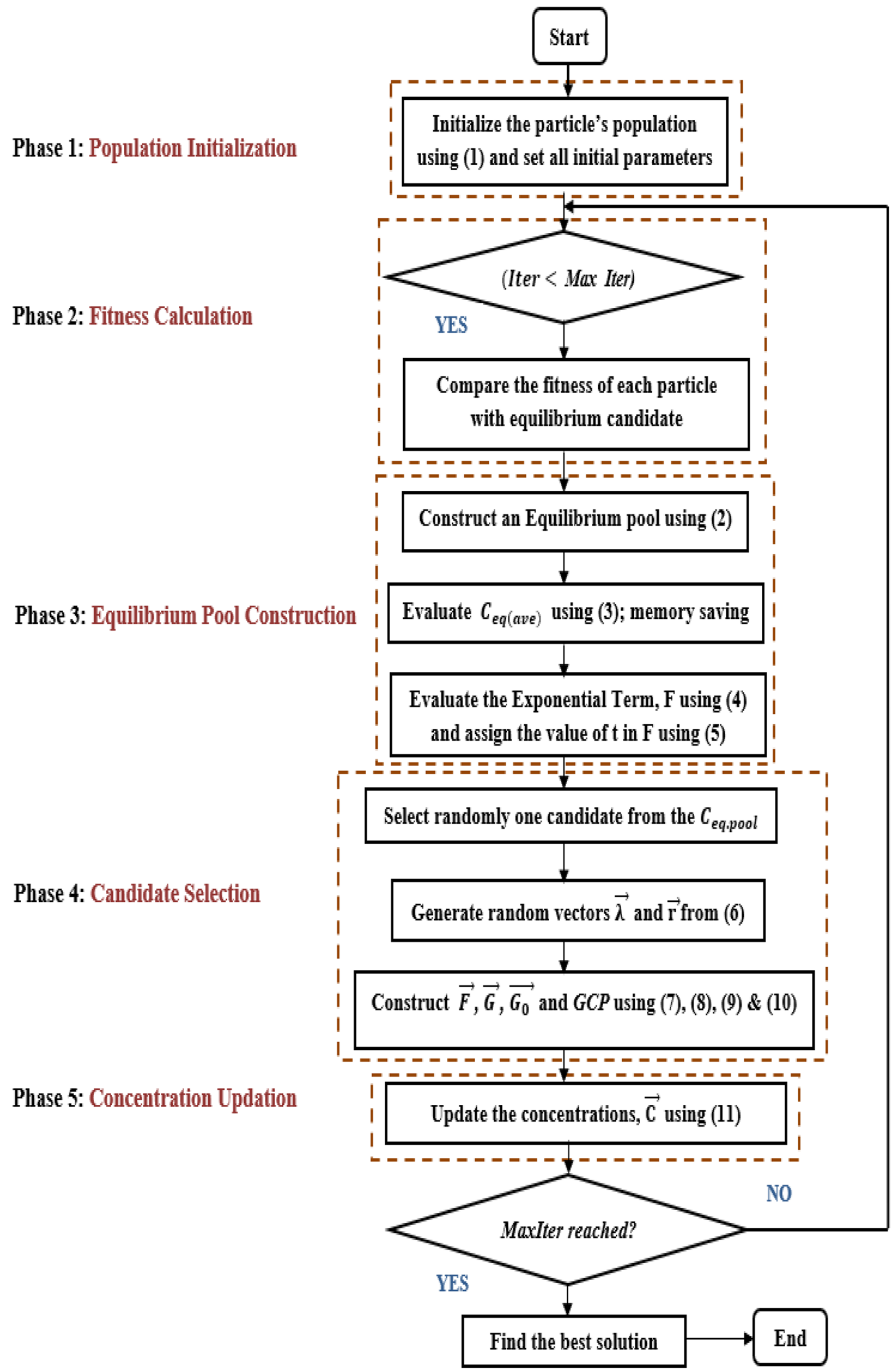


Fig. 7 Flowchart of EO algorithm

Algorithm 1: Pseudocode of the EO algorithm.

Phase 1: Population Initialization Phase

Initialize the population of particles as depicted in **Equation 1.**
Initialize the equilibrium candidate's fitness with a large value.
Initialize free parameters α, β and GP with values 1, 2 and 0.5 respectively.

Phase 2: Fitness Calculation Phase

while (*Iter* < *MaxIter*)
    for *i: 1 to N*
        Compute the fitness of the i^{th} particle
        if (fit ($\vec{C}_i$) < fit ($\vec{C}_{eq1}$)
            Replace $\vec{C}_{eq1}$ with $\vec{C}_i$ and fit ($\vec{C}_{eq1}$) with (fit ($\vec{C}_i$)
        elseif (fit ($\vec{C}_i$) > fit ($\vec{C}_{eq1}$) && fit ($\vec{C}_i$) < fit ($\vec{C}_{eq2}$))
            Replace $\vec{C}_{eq2}$ with $\vec{C}_i$ and fit ($\vec{C}_{eq2}$) with (fit ($\vec{C}_i$)
        elseif (fit ($\vec{C}_i$) > fit ($\vec{C}_{eq1}$) && (fit ($\vec{C}_i$) > fit ($\vec{C}_{eq2}$) && fit ($\vec{C}_i$) < fit ($\vec{C}_{eq3}$))
            Replace $\vec{C}_{eq3}$ with $\vec{C}_i$ and fit ($\vec{C}_{eq3}$) with (fit ($\vec{C}_i$)
        elseif (fit ($\vec{C}_i$) > fit ($\vec{C}_{eq1}$) && (fit ($\vec{C}_i$) > fit ($\vec{C}_{eq2}$) && fit ($\vec{C}_i$) > fit ($\vec{C}_{eq3}$) && it ($\vec{C}_i$) < fit ($\vec{C}_{eq4}$)
            Replace $\vec{C}_{eq4}$ with $\vec{C}_i$ and fit ($\vec{C}_{eq4}$) with (fit ($\vec{C}_i$)
        end ***if***
    end ***for***

Phase 3: Equilibrium Pool Construction Phase

    Construct the Equilibrium Pool, $C_{eq.pool}$ using **Equation 2**
    Evaluate the average of the best four candidates thus far, $C_{eq(ave)}$ using **Equation 3**
    if (*iter* > 1)
        Complete memory saving
    Evaluate the Exponential Term, F using **Equation 4**
    Assign the value of t while evaluating F, using **Equation 5**

Phase 4: Candidate Selection Phase

    for *i: 1 to N*
        Select one candidate randomly from the $C_{eq.pool}$
        Generate $\vec{\lambda}$ and $\vec{r}$ from **Equation 6**
        Construct $\vec{F}$, $\vec{G}$, $\vec{G_0}$ and *GCP* using **Equation 7, 8, 9 and 10**

Phase 5: Concentration Updation Phase

        Update the concentrations, $\vec{C}$ using **Equation 11**
    end ***for***
    Iter=Iter+1
end ***while***

From the summarized details specified in Table 2, it is clear that EO is employed in numerous application areas to resolve several problems. The year-wise depiction of various research articles based on basic or original EO is highlighted in Fig. 8. Also, the full form of each acronym used in Table 2 is tabulated in Table 7.

4 Recent Variants of Equilibrium Optimizer Algorithm

The Equilibrium Optimizer is one of the operational physics-inspired algorithms with an exploratory search mechanism plus a large-scale exploitation mechanism.

Table 2 Summary of the different research work carried out using Basic/Original EO algorithm

Problems/application areas	Year	References	Citation	Publisher
Wind power speed assessment	2023	[64]	3	Elsevier
NPDR classification	2022	[65]	7	Elsevier
Power system networks	2022	[66]	0	IEEE
OPF problem	2022	[67]	1	Springer
TIDFF controllers	2022	[68]	0	IEEE
PV systems	2022	[69]	0	IEEE
Power system problems	2022	[70]	0	IEEE
Fault pole identification	2022	[71]	0	IEEE
Radial distribution system	2022	[72]	5	Elsevier
Perovskite solar cells/PV systems	2022	[73]	2	IEEE
Photovoltaic cells parameter estimation	2022	[74]	0	Elsevier
Reconfiguration of distribution system network	2022	[75]	11	Elsevier
Reconfiguration of power distribution system network	2022	[76]	11	Elsevier
Power flow calculations of power systems	2022	[77]	3	Springer
End-milling process	2022	[78]	0	MDPI
PD controller	2022	[79]	5	Walter De Gruyter Gmbh
PV systems	2022	[80]	4	Elsevier
Stock market prediction	2022	[81]	21	Springer
Feature selection	2022	[82]	0	IEEE
Distribution system	2022	[83]	0	IEEE
Damage detection	2022	[84]	0	Hindawi
Mechanical design problems	2021	[85]	2	Walter De Gruyter Gmbh
Medical image fusion	2021	[86]	2	Semnan University
PV systems	2021	[87]	1	IEEE
Real-world classification problems	2021	[88]	1	IEEE
Local trajectory planning of UGV	2021	[89]	1	Fuji Technology Press Ltd
Optimal allocation in Distributed systems	2021	[90]	23	Wiley
Parameter estimation of solar cells	2021	[91]	14	Elsevier
PEM fuel cell system	2021	[92]	8	Elsevier
Thermoelectric power generation systems	2021	[93]	24	Elsevier
PES in distribution networks	2021	[94]	37	Elsevier
Medical image fusion	2021	[95]	38	Springer
PV systems	2021	[96]	6	O'Reilly and SAGE
Fuel cell dynamic model	2021	[97]	34	Elsevier
Data mining	2021	[98]	12	Elsevier
Sizing of wind turbine Generators in distribution system	2021	[99]	17	Elsevier
Automatic voltage regulator system controller	2021	[100]	34	Elsevier
Medical image fusion	2021	[101]	29	Elsevier
Network reconfiguration and distributed generation allocation in power systems	2021	[102]	86	Elsevier
Magnetic levitation system	2021	[103]	3	IIETA
Renewable energy system	2021	[104]	3	MDPI
Micro-grid power systems	2021	[105]	33	MDPI
Parameters identification of three-diode pv model	2021	[106]	20	IEEE
Optimal design of pv/hydroelectric pumped storage energy system	2021	[107]	1	IEEE
Linear and circular antenna arrays	2021	[108]	6	Cambridge University Press
Hybrid pv/wind/diesel/battery microgrid	2021	[109]	33	IEEE
Feature selection	2021	[110]	1	Springer
Brushless direct current wheel motor design problem	2021	[111]	17	Tech Science Press
PV inverter control	2021	[112]	5	IEEE

Table 2 (continued)

Problems/application areas	Year	References	Citation	Publisher
Wind turbine	2021	[113]	2	WSEAS
Traveling salesman problem	2021	[114]	2	INASS
Wind generation units and solar photovoltaic systems	2021	[115]	5	Taylor & Francis
VAC system	2021	[116]	11	Elsevier
Wind energy control System	2021	[117]	4	Elsevier
Rainfall-runoff modelling	2021	[118]	15	MDPI
Forecasting and eliminating tremors in teleoperation	2021	[119]	7	Elsevier
Renewable micro-grids	2021	[120]	10	MDPI
Solar dish collector	2021	[121]	25	Elsevier
Economic dispatch problem	2020	[122]	21	IEEE
Schottky diode parameter estimation	2020	[123]	26	Elsevier
Hybrid AC/DC grids	2020	[124]	49	Elsevier
Micro-grid power systems	2020	[125]	8	IEEE
OPF problems	2020	[126]	16	MDPI
Interconnected power systems	2020	[127]	11	SEP
Traffic transportation prediction	2020	[128]	28	Elsevier
MANET	2020	[129]	5	Springer
Prediction of laser cutting parameters	2020	[130]	70	Springer
Power systems	2020	[131]	35	Wiley

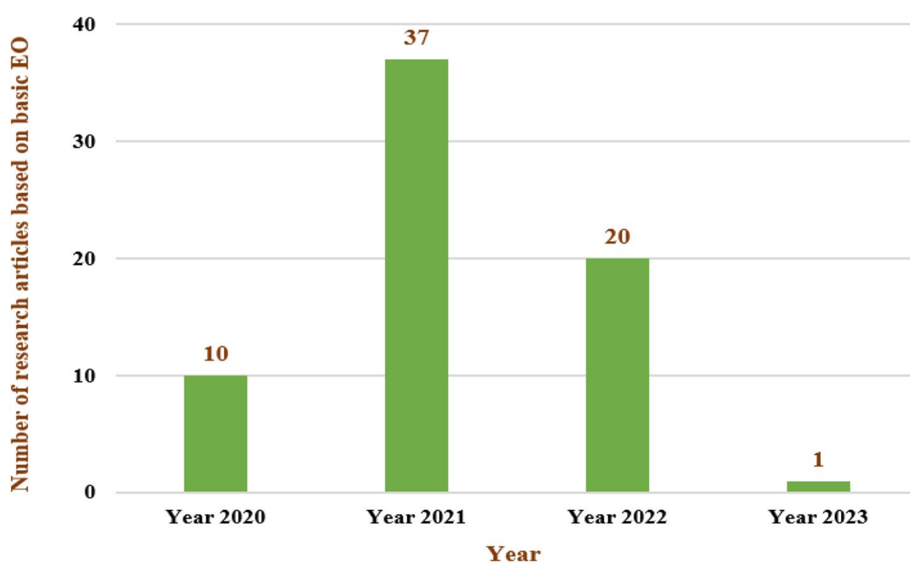


Fig. 8 Year-wise depiction of the various research article based on Basic EO (As per the survey)

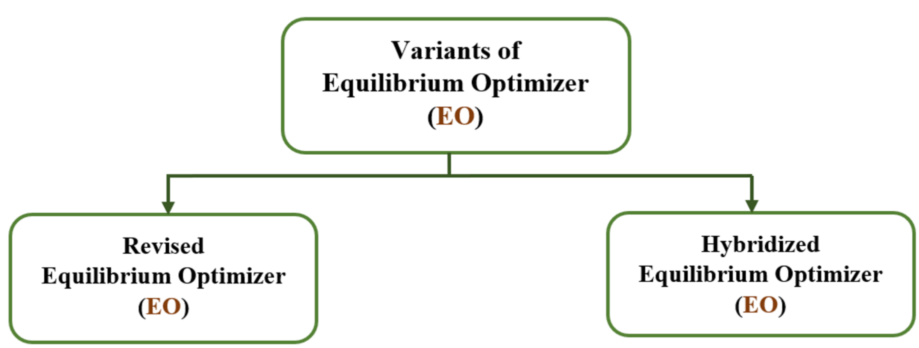


Fig. 9 Revised and Hybridized variants of EO

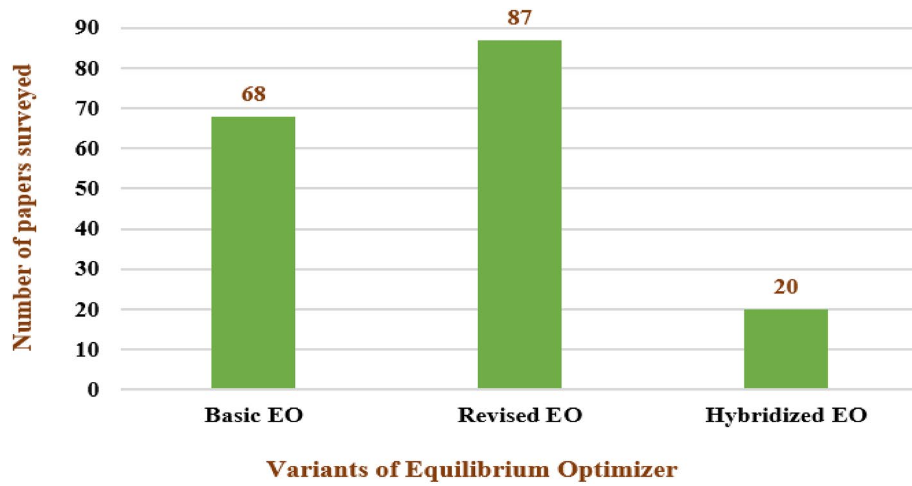


Fig. 10 Year-wise depiction of the various research article based on Basic EO and variants of EO (As per the survey)

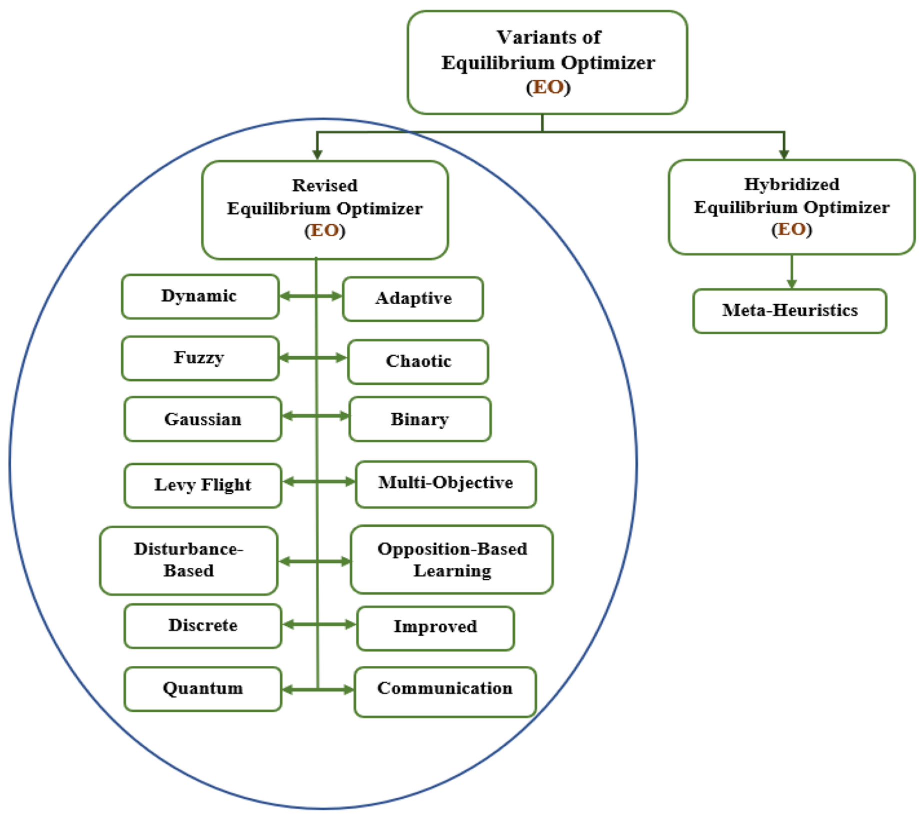


Fig. 11 Different revised variants of EO

Primarily, however, it has been proposed and expected to explore and exploit continuous search spaces to address continuous optimization problems. On the one hand, for a unimodal function, the stability of EO is comparatively decent in optimization and the main reason for this is the existence of a generation rate. On the other hand, standard EO lacks immature stability in exploration and utilization during the process of optimizing multimodal functions. EO has the tendency to effortlessly get trapped in local minima, thus leading towards meagre stability and ruining the overall performance of EO, which requires improving EO. Therefore, with time, though the EO algorithm is just three years old, several researchers paved the way towards revising the basic EO so that it could be adjusted to meet the requirements of different search spaces along with its application beyond the continuous optimization problems. In simple words, EO is revised to not just obtain a better/optimal solution but also to improve its searching rules. The alteration is proposed in two variants, namely, Revised and Hybridized, and the same is depicted in Fig. 9. The number of articles surveyed related to basic EO, revised EO, and hybridized EO is depicted in Fig. 10.

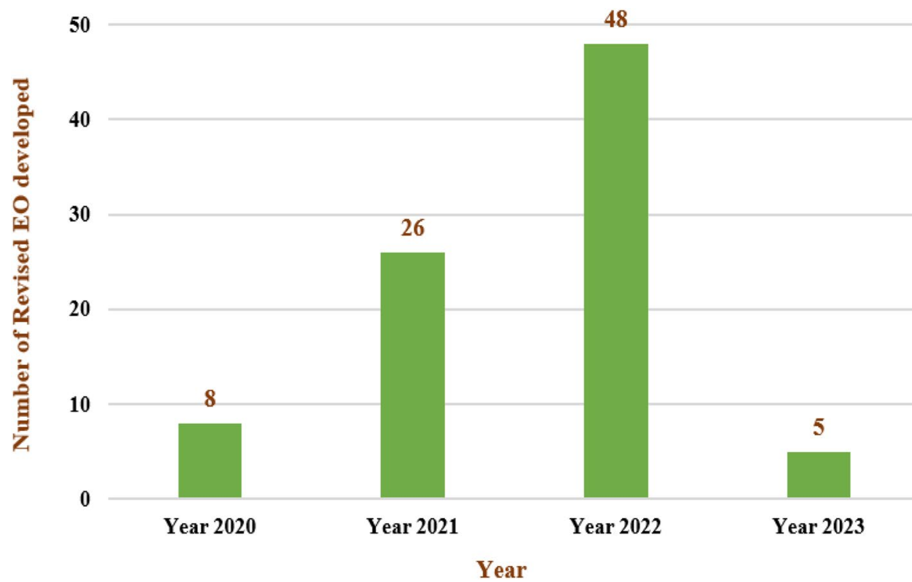


Fig. 12 Year-wise depiction of the various research article based on revised variants of EO (As per the survey)

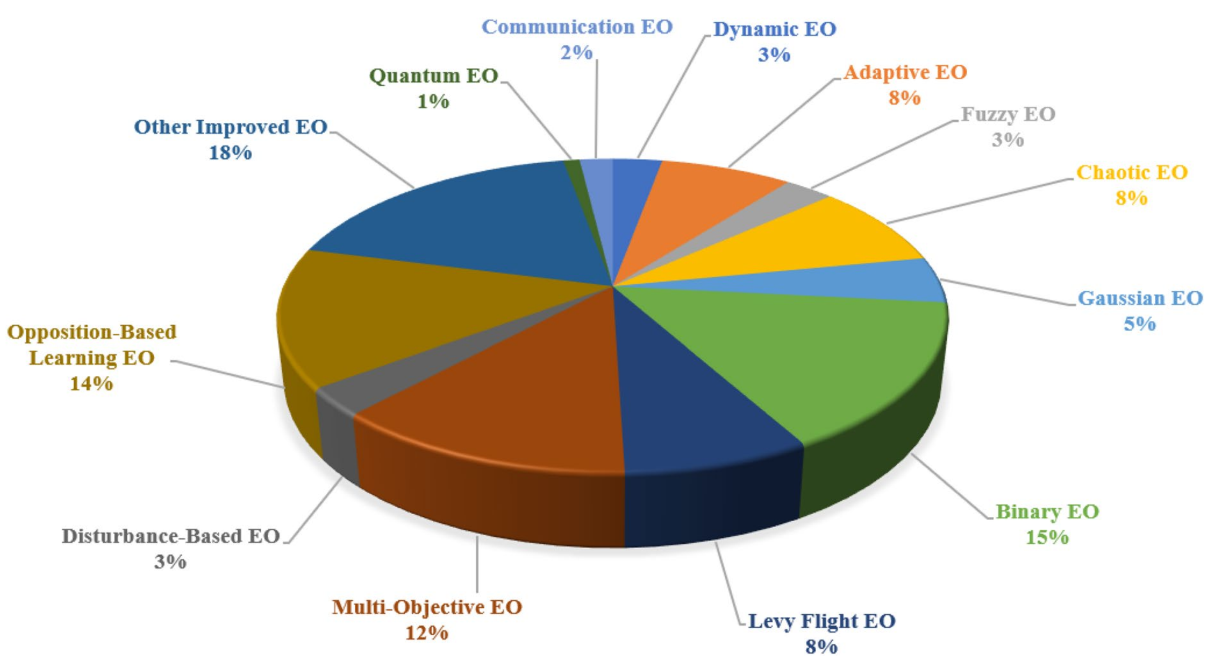


Fig. 13 Proportions of research articles addressing the various types of revised EO. (As per the survey)

The following subsections provide relevant work on the various variants of EO and a summary of each variant in tabular form.

4.1 Revised Variants of Equilibrium Optimizer (EO)

Compared to basic or original EO, revised variants of EO are usually developed by layering specific additional strategies on top of existing EO, thus solving a wide range of complex optimization problems in the real world. Figure 11 shows the various revised variants of the EO and Fig. 12 shows the annual presentation of various published research papers on revised EO.

The description of the research articles that deals with the introduction of various categories of the revised variants, namely Dynamic, Adaptive, Fuzzy, Chaotic, Gaussian, Binary, Levy-Flight, Multi-Objective, Disturbance-Based, Opposition-Based Learning, Improved, Quantum and Communication is discussed further and the same has been highlighted in Fig. 13.

4.1.1 Dynamic Equilibrium Optimizer

In order to increase the effectiveness of the ordinary EO, He et al. presented the Improved Equilibrium Optimizer (IEO) in 2022 [132]. The IEO combines the chaotic initialization technique with the dynamic sine and cosine components. Additionally, the experimental findings unmistakably demonstrate that the proposed IEO outperforms other current algorithms, opening the door for both financial and environmental advantages in the operation of the power system. Improved Equilibrium Optimizer (IEO), a revised version of EO proposed by Lan et al. in 2022 [133], uses a chaotic equilibrium pool to improve information interaction, a nonlinear dynamic generation strategy to balance global and local abilities, and a golden sine strategy to update and avoid local optimums. This revision of EO improves on standard EO's performance overall. Additionally, the experimental findings unmistakably show that the suggested IEO outperforms m-EO, AEO, OB-L-EO, and HEO for the optimal power flow problem. A new version of EO known as the United Equilibrium Optimizer (UEO), which uses combined parameters in the equilibrium pool (EOU) and dynamic parameters (EOD) to provide balance in standard EO, was proposed by Gui et al. in the year 2021 [134]. Furthermore, it is abundantly obvious from the experimental results that for multimodal image registration, the suggested UEO performs better than PSO, GWO, GA, GSA, SSA, and CMA-ES.

4.1.2 Adaptive Equilibrium Optimizer

Self-Adaptive Quantum Equilibrium Optimizer with Artificial Bee Colony (SQEOABC) is a new variant of revised and hybridized EO that Zhong. et al. proposed in 2023 [135]. It incorporates quantum theory and self-adaptive mechanisms into the EO's updating rule for convergence enhancement and further uses the updating mechanism of ABC to arrive at the right solution. Additionally, the experimental results clearly show that the proposed SQEOABC performs better than various state-of-the-art metaheuristics such as PSO, CMAES, GWO, SSA, HHO, SMA, WSO, TLSMA, DDSRPSO, EESHHO, and LSHADE-cnEpSin for COVID-19 feature selection problem. In order to ensure the proper balance and transition between exploration and exploitation and to further improve the convergence rate towards reaching the near-optimal region, Houssein et al. in the year 2022 [136] proposed a new variant of revised EO referred to as Self-Adaptive Equilibrium Optimizer (self-EO). This algorithm incorporates the strategies namely exploration/exploitation balancing, self-adaptive control parameters, and population reduction. Additionally, the experimental results clearly show that the suggested self-EO beats other state-of-the-art metaheuristics, such as EO, SCA, GSA, HHO, AGSK, IMODE, TLBO, and PSO, demonstrating its effectiveness in global, combinatorial, engineering, and multi-objective issues. Equilibrium Optimizer with Divided Population (DEO), which Li et al. proposed in 2022 [137], is a new variation of the revised EO that incorporates the adaptive population division strategy with beta distribution, distance factor, and disturbance factor to improve the standard EO and balance exploration and exploitation while enhancing convergence and breaking out of local optimum. Additionally, the experimental findings clearly reveal that the proposed LWMEO outperforms other current state-of-the-art metaheuristics, demonstrating its effectiveness in a variety of feature selection challenges. Hybrid Equilibrium Optimizer with Capsule Auto Encoder (HEOCAE), which incorporates skull stripping, Normalized Linear Smoothing and Median Joint (NLSMJ) filtering, an adaptive Fuzzy based Atom Search Optimizer, Adaptive Rain Optimization, and capsule auto encoder at different stages to enhance the standard EO, was proposed by Ansingkar et al. in the year 2022 [138]. Also, the experimental results clearly reveal that the proposed HEOCAE performs better than EO and other current state-of-the-art metaheuristics, demonstrating its effectiveness in the Multi class Alzheimer detection challenge. In 2022 [139], Das et al. developed a new version of EO called the Adaptive Equilibrium Optimizer (AEO), which uses a non-Entropic objective function and an adaptive decision-making mechanism to improve traditional EO. Furthermore, it is amply understandable from the experimental results that, for multilayer optimum threshold selection issues, the proposed AEO outperforms AEO-Tsallis and AEO-Otsu. The Automata-based Improved Equilibrium Optimizer with U-shaped Transfer Function (AIEOU), which Ahmed et al. suggested in 2021 [140], uses learning-based automata, a U-shaped transfer function, and adaptive hill climbing to improve standard EO. Furthermore, it is abundantly obvious from the experimental findings that the proposed AIEOU outperforms SSD + LAHC, RTHS, A BSF, HSGW, RSGW, ASGW, BGA, and PSO in terms of feature selection. An updated version of EO called the Adaptive Equilibrium Optimizer (AEO), which employs interdependence-based approaches and adaptive decision making to improve the standard EO, was proposed by Wunnava et al. in the year 2020 [141]. Additionally, experimental results show that the suggested AEO offers greater performance for multilevel thresholding when compared to EO, GWO, WOA, SSA, and WDO.

4.1.3 Fuzzy Equilibrium Optimizer

Hybrid Equilibrium Optimizer with Capsule Auto Encoder (HEOCAE), which incorporates skull stripping, Normalized Linear Smoothing and Median Joint (NLSMJ) filtering, an Adaptive Fuzzy based Atom Search Optimizer, Adaptive Rain Optimization, and capsule auto encoder at different stages to enhance the standard EO, was proposed by Ansingkar et al. in the year 2022 [138]. Also, the experimental results clearly reveal that the proposed HEOCAE performs better than EO and other current state-of-the-art metaheuristics, demonstrating its effectiveness in the Multi class Alzheimer detection problem. The Hybrid Fuzzy Equilibrium Optimizer (HFEO), which incorporates fuzzy-based fitness functions to improve the standard EO, was proposed by Yehia et al. in 2022 [142]. Also, it is profusely clear from the results of the experiment that proposed HFEO performs better than GWO, MFO, FPA, GOA, HFEO, and PSO when it comes to estimating the size and position of distributed generators. Modified Equilibrium Optimization Algorithm-based Interval Type-2 Fuzzy Proportional Integral Derivative Controller (MEO-IT2FPID), which combines IT2FPID to lessen the frequency control issue and some scaling factor into regular EO, was proposed by Khadanga et al. in 2021 [143]. Additionally, the experimental findings unmistakably show that the suggested CSED-OEO approach outperforms EO, WOA, and MWOA in terms of frequency control of an AC microgrid.

4.1.4 Chaotic Equilibrium Optimizer

Agarwal et al. in 2022 [144] proposed a new variant of revised EO termed as Normalized Mutual Information-based equilibrium optimizer (NMIEO) that incorporates the local search strategy on Normalized mutual information and chaotic maps to boost the exploitation ability and diversity of the problem as well as enhance the population initialization of the standard EO. Further, the experimental result evidently highlights that the proposed NMIEO outperforms other state-of-the-art metaheuristics showcasing its efficacy in feature selection domain. In order to increase the effectiveness of the ordinary EO, He et al. presented the Improved Equilibrium Optimizer (IEO) in the year 2022 [132]. The IEO combines the chaotic initialization technique with the dynamic sine and cosine parameters. Additionally, the experimental findings unambiguously illustrates that the proposed IEO surpasses other current algorithms, paving the way for the operation of the power system to be both economical and environmentally friendly. Improved Equilibrium Optimizer (IEO), which Lan et al. proposed in 2022 [133], is a revised version of the equilibrium optimizer that uses chaotic equilibrium pool to improve information interaction, nonlinear dynamic generation strategy to balance global and local ability, and golden sine strategy for updating and avoiding local optimum to improve standard EO's performance overall. Additionally, the experimental findings distinctly show that the suggested IEO outperforms m-EO, AEO, OB-L-EO, and HEO for the optimal power flow problem. Disturbance-Inspired Equilibrium Optimizer (DIEO), an updated version of EO proposed by Wang et al. in 2022 [145], uses chaotic sequence and excellent nodes set theory as deterministic and stochastic components to improve traditional EO. Furthermore, the experimental findings unequivocally illustrate that proposed DIEO outperforms EO, AOA, HGS, and AGPSO for the acquisition of hydrogeological parameters. In order to improve the standard EO, Sayed et al. introduced the Chaotic Equilibrium Optimizer Algorithm (CEO) in 2022 [146]. CEO uses eight alternative S-shaped and V-shaped transfer functions. Additionally, the experimental findings clearly highlight that the suggested CEO performs better than EO, PSO, QABC, CSO, ALO, SSA, ASO, and BOA for problems involving feature selection and global optimization. Mousa et al. in 2021 [147] proposed a revised variant of EO termed Chaotic Search based Constrained Equilibrium Optimizer Algorithm (CS-CEA) that incorporates Exhaustive local search, chaos-based search algorithm to enhance the standard EO. Further, experimental results clearly highlight that proposed CS-CEOA method provides superior performance when compared with GA and PSO, for Non-Linear Programming and Petrochemical application. The Enhanced Equilibrium Optimization (E^2O) Algorithm, which uses Fractional Order Chaotic (FOC) system models and controller parameter optimization, was proposed by Ates et al. in the year 2021 [148]. Further, experimental results clearly highlight that proposed E^2O method provides superior performance when compared with EO for Engineering problems. Improved Equilibrium Optimizer (IEO), a modified version of EO introduced by Lan et al. in 2021 [149], uses chaotic mechanisms for population range expansion, adaptive weights, and an adaptive convergence factor to prevent becoming caught in local optima, improving the power of standard EO. Additionally, experimental results demonstrate that the suggested IEO approach for the LSTM Neural Network outperforms PSO, GWO, SOA, WOA, CSA, MPA, COA, CPA, TSA, and GA. In order to improve the performance of the ordinary EO, Zheng et al. suggested the Chaotic Equilibrium Optimizer Algorithm (CEOA) in the year 2020 [150], CEOA uses tent maps and the chaos approach. Additionally, experimental results unmistakably show that as compared to original EO, the suggested CEOA offers greater performance for the optimization of traditional benchmark functions.

4.1.5 Gaussian Equilibrium Optimizer

Extreme Learning Machine Modified Equilibrium Optimizer (ELM-MEO), which Bardhan et al. suggested in the year 2022 [151], incorporates Gaussian mutation with the aid of an exploratory search mechanism and ELM to create and optimize the learning parameters of standard EO.

Additionally, the experimental results clearly reveal that the proposed ELM-MEO outperforms other state-of-the-art metaheuristics like EO, HHO, SMA, and MPA, demonstrating its effectiveness in predicting soil compression index, particularly for roads, railroads, and airport runways. In order to improve the standard EO, Abdel et al. proposed the MOEO-EED-G, OMOEO-EED-G revision of EO in 2021 [152]. This revision incorporates the Crowding Distance Approach, Linear and Non-Linear Equations, Exploration–Exploitation Dominance Strategy, Gaussian-based Mutation (G) Strategy, and Opposition-Based Learning. Additionally, experimental results show that the suggested method outperforms MOEOL, MOEOC, MOEOLog, MOEOT, SMPSO, NS GAII, NSGAIII, PAES2, SMSEMOA, ASMSEMOA, ANSGAII, and ANSGAIII for the optimization of benchmark functions. An improved version of EO known as the Multiple Population Hybrid Equilibrium Optimizer (MHEO), which uses Lévy flight and the inferior solution shift technique to minimize stagnation, was developed by Tang et al. in the year 2021 [153]. Additionally, experimental results demonstrate that the proposed MHEO technique for UAV path planning outperforms EO, MPA, SMA, VCS, GEDGWO, and HFPSO. The modified Equilibrium Optimizer (m-EO), which Gupta et al. introduced in 2020 [154], uses Gaussian mutation based on population division and reconstruction to increase the standard EO's rate of convergence. Additionally, experimental results show that, when compared to GWO, SCA, SSA, OBSCA, OBGWO, PSO, and FA for numerical optimization, m-EO offers greater performance.

4.1.6 Binary Equilibrium Optimizer

In 2022 [155], Faramarzi et al. developed a new version of the improved EO known as the Binary Equilibrium Optimizer (BiEO), which includes the benefits of velocity-based approaches by redesigning discrete binary issues using a V-shape transfer function and tweaking the traditional EO. Additional evidence of the proposed BiEO's effectiveness in optimum control issues comes from the experimental results, which clearly show that it outperforms other state-of-the-art metaheuristics including BPSO/S, BPOS/V, BDA, and GA. ReliefF Binary Equilibrium Optimizer with Local Search (RBEO-LS), which was proposed by Quadfel et al. in the year 2022 [156], is a new variants of revised EO that incorporates the ReliefF filter method as a population strategy to reduce the search space and Binary EO with Local Search strategy as a wrapper mechanism to speed up EO's convergence speed. The experimental results also clearly show that the proposed BiEO beats various cutting-edge metaheuristics, such as EO, SSA, SCA, DE, BAT, BPSO, and HGSO, demonstrating its effectiveness in the feature selection area. In 2022 [157], Varzaneh et al. proposed a new revision of the EO called the Binary Improved Equilibrium Optimizer (BIMEO), which incorporates the strategies mRMR, Wrapper feature selection approach, Entropy-based and Levy-flight operators to prevent the standard EO from becoming stuck in a local optimum and thereby balancing the exploration and exploitation mechanism. Additionally, the experimental results evidently disclose that the proposed BIMEO performs better than other contemporary state-of-the-art metaheuristics, demonstrating its effectiveness in Feature Selection issues. With the purpose of improving the traditional EO, Minocha et al. in the year 2022 [158] devised the AV- Binary Modified Equilibrium Optimizer (AV-BMEO), which combines the AV-shape transfer function, opposition-based learning, and k-nearest neighbour classifier. The experimental results also clearly reveal that the proposed AV-BMEO performs better than other current state-of-the-art metaheuristics, demonstrating its effectiveness in Feature Selection. The ReliefF-guided Novel Binary Equilibrium Optimizer (RG-NBEO), which Zhang et al. proposed in 2022 [159], combines SSr and VVr transfer functions based on opposition learning with ReliefF bootstrapping strategy to achieve good stability between exploration and exploitation and to convert the continuous search space into a binary search space. Additionally, it is clear from the experimental results that the proposed RG-NBEO surpasses other current state-of-the-art metaheuristics when projecting its effectiveness in Feature selection problem. Binary Modified Equilibrium Optimizer (BMEO), which integrates Band selection and V-shape transfer function to maintain the balance between exploration and exploitation and further improves the exploration ability of conventional EO, was proposed by Minocha et al. in the year 2022 [160]. Also, it is clear from the experimental results that the proposed BMEO performs better than contemporary state-of-the-art metaheuristics when projecting its effectiveness in hyperspectral image classification. The Novel Discrete Equilibrium Optimizer algorithm (NDEOA), which was proposed by Haouassi et al. in the year 2022 [161], is a new variation of the revised EO that incorporates discrete particle encoding as well as new discrete operators for defining the classification rule and for updating the particle's position in a discrete search space. Also, the experimental data clearly shows that the suggested NDEOA attained good levels of accuracy, sensitivity, and specificity and may thus be successfully applied to the generation of classification rules. Mohamed et al. in the year 2022 [162] proposed a revised variant of EO termed as Binary version of the Equilibrium Optimization Algorithm (BEOA) that incorporates binary encoding mechanism. Further, the experimental results clearly highlight that proposed O-LEO has superior performance when compared with BGWO, BPOS, BWOA, BSMO, BGO and BAEO and BEHO proving its significance in domination metric dimension problem. In 2022 [163], Hu et al. introduced an updated version of EO called the Binary version of the Equilibrium Optimizer (BEO), which only improves the standard EO by changing the equilibrium concentration and position updation equation. Also, the experimental findings unmistakably show that proposed BEO outperforms BBA, BDE, BGWO, BPOS, and BPSOGSA for Feature Selection. Using a Discrete Equilibrium Optimization Algorithm (DEOA-CRM) that incorporates Sequential Covering Strategy for Classification Rule Mining and Discrete operators to improve the performance of standard EO, Malik et al. proposed a revised variant of EO called Classification Rule Mining in the year 2022 [164]. Furthermore, the experimental findings distinctly show that the proposed I-EO outperforms DEOA-CRM, ACO/PSO 2, cAnt-MinerPB, Ant-MinerPAE, and ILS-AntMiner in terms of generating classification rules. With the aim to improve upon the traditional EO, Guha et al. suggested Discrete Equilibrium Optimizer Simulated Annealing (DEOSA) in the year 2022 [165]. DEOSA integrates U-shaped transfer function and SA for local search technique. Additionally, it is amply understandable from the experimental findings that the proposed DEOSA outperforms DEO, GA, PSO, GSA, BBA, bALO-S, bALO-V, HGSA, CPBGSA, and DGA for Feature Selection. Rahab et al. in the year 2022 [166] proposed a revised variant of EO named as Binary Equilibrium Optimization Algorithm (BEOA) that permits BEOA to perform Classification rule extraction. Further, it is profusely comprehensible from the experimental results that proposed BEOA has superior performance when compared with PART, RIPPER, OneR, C4.5, REPTree, SVM, K-NN and NB for sentiment analysis. Improved Binary version of the Equilibrium Optimizer Algorithm (IBEO), which employs Opposition Based Learning and Local search algorithm to increase population variety and optimize the exploitation of conventional EO, was proposed by Elmanakhly et al. in the year 2021 [167]. Additionally, the experimental findings unambiguously illustrate that the proposed IBEO outperforms PSO, GOA, GWO, WOA, DA, and ISSA for the feature selection problem. With the intention to improve the performance of traditional EO, Abdel et al. created Binary version of Equilibrium Optimization (BEO) in the year 2021 [168]. This improved version of EO includes eight transfer functions, including V-shaped and S-shaped, a penalty function, and the Repair Algorithm (RA). Also, the experimental findings demonstrate that proposed BEO outperforms EOS2, SA, GA, IGA-SA, GSA, and BB for the 0–1 Knapsack Problem. The Binary Equilibrium Optimizer Algorithm based on S and V Transfer function (BEO-S and BEO-V) and Equilibrium Optimizer Algorithm based on Target (BEO-T) employ S and V Transfer function and target dimension values to improve the standard EO, respectively, and were proposed by Gao et al. in the year 2020 [169]. Additionally, experimental results show that, when compared to other metaheuristic algorithms like BGOA, BGWO, and BPSO in the largest number of datasets for feature selection problems, BEO-V2 offers greater performance among the suggested approaches.

4.1.7 Levy-Flight Equilibrium Optimizer

In the year 2022 [170], Liu et al. proposed a new variant of revised and hybridized EO called the Levy Whale Optimization Mutation Equilibrium Optimizer (LWMEO), which combines the random walk strategy based on Lévy flight, the spiral encirclement mechanism of WOA, and the adaptive proportional mutation strategy to increase search range and exploration ability, exploitation ability, and speed up the convergence speed of the standard EO. The experimental results also evidently show that the proposed LWMEO performs better than existing state-of-the-art metaheuristics including EO, AEO, IEO, SSA, MSSA, and JADE, demonstrating its effectiveness in many engineering fields. Varzaneh et al. in the year 2022 [157] proposed a new variant of the EO called the Binary Improved Equilibrium Optimizer (BIMEO), which incorporates the strategies namely, mRMR, Wrapper feature selection approach, Entropy-based and Levy-flight operators to prevent the standard EO from becoming stuck in a local optimum and thereby balancing the exploration and exploitation mechanism. Additionally, the experimental results clearly reveal that the proposed BIMEO performs better than other contemporary state-of-the-art metaheuristics, demonstrating its effectiveness in Feature Selection problem. Modified Equilibrium Optimizer (MEO), which incorporates Iterative Cosine Operator (ICO), Levy flight, and heavy-tailed non-uniform levy distribution to reduce diversification to intensification and improve the exploration and exploitation ability of standard EO, was proposed by Minocha et al. in the year 2022 [171]. The experimental results evidently highlights that the proposed MEO works better than EO and other state-of-the-art metaheuristics, demonstrating its effectiveness in engineering problems. Levy Equilibrium Optimizer (LEO), a new variation of revised EO that incorporates the Levy flight update strategy to improve standard EO, was proposed by Aval et al. in the year 2022 [172]. Additionally, the experimental results clearly confirms that the proposed LEO performs better than EO and other contemporary state-of-the-art metaheuristics, including PSO, GWO, GA, GSA, and SSA, demonstrating its effectiveness in DNA storage. Improved Equilibrium Optimizer based on Levy Flight (IEOLV), which incorporates Levy flight method to eliminate local minimum stagnation and hence improves convergence efficiency of the standard EO, was proposed by Balakrishnan et al. in the year 2022 [173]. Additionally, it is clear from the experimental results that the proposed IEOLV outperforms EO and other current state-of-the-art metaheuristics when projecting its effectiveness in Feature Selection problem. Mostafa et al. in the year 2021 [174] proposed a revised variant of EO termed as Levy Spiral Flight Equilibrium Optimizer (LSFEO) that employs Levy Flight distribution to avoid stagnation and spiral motion of the particles to boost exploitation in standard EO. Further, experimental outcome evidently disclose the proposed CSED-OEO method provides superior performance when compared with EO, KHA, SKHA, ARCBBO, ABC, TLBO, MTLBO, GOA and AGOA for Optimal Power Flow (OPF) problem. An improved version of EO known as the Multiple Population Hybrid Equilibrium Optimizer (MHEO), which uses Lévy flight and the inferior solution shift technique to minimize stagnation, was developed by Tang et al. in the year 2021 [153]. Additionally, experimental results demonstrate that the proposed MHEO technique for UAV path planning outperforms EO, MPA, SMA, VCS, GEDGWO, and HFPSO. The Enhanced Equilibrium Optimization Algorithm with Levy Flight (Levy EOA), which Zhao et al. proposed in 2020 [175], uses levy flight to improve the performance of standard EO. Additionally, the experimental findings clearly show that the proposed Levy EOA outperforms PSO, BA, and GWO for the optimization of unimodal, multimodal, and the bottom flat-like benchmark functions.

4.1.8 Multi-Objective Equilibrium Optimizer

Improved Multi-objective Equilibrium Optimizer (IMOEO), which integrates the techniques of optimal PV energy consumption approach, limited non-dominant mechanism, and TOPSIS to improve the performance of conventional EO, was proposed by Yi et al. in the year 2022 [176]. Also, the experimental results clearly reveal that the proposed IMOEO works better than other contemporary state-of-the-art metaheuristics, demonstrating its effectiveness in residential housing scheduling. Abou et al. in the year 2022 [177] proposed a new variant of revised EO termed as Multi-objective Equilibrium Optimization technique (MOEOT) that incorporates Pareto optimal front and fuzzy concept to extract the best solution to enhance the power of standard EO. Further, the experimental result noticeably highlights that the proposed MOEOT outperforms EO and other recent state-of-the-art metaheuristics projecting its efficacy in Radial distribution system. In order to improve the performance of standard EO, Yi et al. proposed a new variant of revised EO in 2022 [178] called Multi-Objective Equilibrium Optimizer algorithm integrated Competition Mechanism (CMOEO). This variant incorporates Competition mechanism integrating Differential Evolution by swapping out the constant factors of exploration and exploitation with dynamic factors. Also, it is clear from the experimental results that the proposed CMOEO beats EO and other state-of-the-art metaheuristics estimating its effectiveness in Photovoltaic Energy Storage Systems. R_2 index hybrid multi-objective equilibrium optimization algorithm (R_2HMEOA), which includes R_2 index and elite archiving method, was proposed by Yu et al. in the year 2022 [179] in order to improve the rules of Pareto solution, reference point strategy, and to increase the standard EO. Also, it is profusely obvious from the experimental findings that the suggested R_2HMEOA outperforms NSGA-II, NSGA-III, MOSHO, and MOEA for the Mine Ventilation system. Premkumar et al. in the year 2022 [180] proposed a revised variant of EO termed as Multi-Objective Equilibrium Optimizer Algorithm (MOEO) that incorporates crowding distance mechanism, non-dominated sorting strategy and an archive with an update function to balance exploration and exploitation phase, preserve population diversity and uphold and improve the coverage of Pareto with optimal solutions. Further, the experimental results clearly highlight that proposed MOEO has superior performance when compared with NSGAII, MOEA/D and MOPSO for Multi-Objective Optimization Problems. Constrained Multiobjective Equilibrium Optimizer Algorithm (CMEO), which employs Pareto border minimization and Repair method to improve conventional EO for Combined Economic Emission Dispatch Problem (CEEDP), was proposed by El et al. in the year 2021 [181]. Additionally, it is obvious from the experimental findings that the suggested CMEO outperforms DRN-PSO, NSGA, NPGA, FCPSO, MSFLA, RCGA, and SPEA. In order to improve the standard EO, Abdel et al. proposed the revised variant MOEO, MOEOS, MOEO-EED, MOEO-EED, and OMOEO-EED-G in the year 2021 [152]. This variant incorporates the Crowding Distance Approach, Linear and Non-Linear Equations, Exploration–Exploitation Dominance Strategy, Gaussian-based Mutation (G) Strategy, and Opposition-Based Learning. Additionally, experimental results show that the suggested method outperforms when compared to MOEOL, MOEOC, MOEOLog, MOEOT, SMPSO, NS GAII, NSGAIII, PAES2, SMSEMOA, ASMSEMOA, ANSGAII, and ANSGAIII considering many benchmark functions. The Multi-objective Equilibrium Optimizer Algorithm (MEOA), which uses the Improvement-Based Reference Points Method (IBRPM) to improve the standard EO by boosting population diversity and accelerating convergence speed, was proposed by Abdel et al. in the year 2021 [182]. Additionally, experimental results demonstrate that the proposed MEOA technique outperforms other multi-objective optimization methods such as CDG, LMOCSO, LMEA, CMOPSO, CTAEA, CAMOEA, CMOEAD, AGEMOED, and ARMOEA. Disruption-based Multi-Objective Equilibrium Optimization Algorithm (DMOEOA), which employs Layered Disruption technique and disruption operators to improve the exploration and exploitation capabilities of the standard EO, was proposed by Chen et al. in the year 2020 [183]. Additionally, experimental findings demonstrate that the suggested BEO technique outperforms MOPSO, MOALO, MOWOA, NSGAII, and MOGWO for structural optimization issues.

4.1.9 Disturbance-Based Equilibrium Optimizer

Disturbance Inspired Equilibrium Optimizer (DIEO), which Wang et al. proposed in the year 2023 [184], is a new variation of the revised EO that incorporates the strategies of disturbance-based hybrid initialization, boundary check, and an adaptive global position disturbance approach that materially enhances the exploration and exploitation capability of the standard EO. Additionally, the experimental results clearly reveal that the proposed DIEO performs better than other state-of-the-art metaheuristics including EO, ASO, HFPSO, LHHO, HGS, and IGWO, demonstrating its effectiveness in a variety of real-world engineering issues. Wang et al. in the year 2022 [145] proposed a revised variant of EO termed as Disturbance-Inspired Equilibrium Optimizer (DIEO) that employs good nodes set theory and chaotic sequence as deterministic and stochastic components to enhance standard EO. Further, the experimental results clearly highlight that proposed DIEO has superior performance when compared with EO, AOA, HGS and AGPSO for Acquisition of Hydrogeological parameters. In order to balance exploration and exploitation in standard EO, Shao et al. proposed the Interswarm Interactive Learning Strategy Equilibrium Optimizer (IILEO) in the year 2021 [185]. IILEO uses the softmax method, Interswarm Interactive Learning, a global optimal disturbance strategy, and linearly decreasing inertia weights. Also, the experimental findings unmistakably show that proposed IILEO outperforms EO, PSO, GWO, and WILEO 4 for the UAV path planning problem.

4.1.10 Opposition-Based Learning Equilibrium Optimizer

Ameliorated Equilibrium Optimizer (AEO), which Wu Zhong et al. proposed in 2023 [186], is a new variation of the revised EO that incorporates the strategies Opposition-Based Learning, Centroid Opposition-Based Learning, and Self-learning strategies to improve the optimization performance of the standard EO by using various information about the opposite and neighbourhood spaces as well as about the entire population present in the search space. The experimental result also demonstrates the effectiveness of the proposed AEO in path planning for the Unmanned Ground Vehicle (UGV) problem, outperforming other state-of-the-art metaheuristics like EO, PSO, GWO, and SSA. Information-utilization Strengthened Equilibrium Optimizer (IS-EO), which Zhang et al. proposed in the year 2022 [187], incorporates the strategies of information guiding using the local and global best opposition learning and differential mutation strategy to construct and strengthen the information sharing among individuals. Additionally, the experimental results clearly reveal that the proposed IS-EO performs better than other contemporary state-of-the-art metaheuristics, demonstrating its effectiveness in Engineering design issues. Minocha et al. in the year 2022 [158] proposed a new variant of revised EO termed as AV- Binary Modified Equilibrium Optimizer (AV-BMEO) that incorporates AV-shape transfer function, opposition-based learning, k-nearest neighbor classifier to enhance the standard EO. Further, the experimental result evidently highlights that the proposed AV-BMEO outperforms other recent state-of-arts metaheuristics showcasing its efficacy in Feature Selection. The ReliefF-guided Novel Binary Equilibrium Optimizer (RG-NBEO), which Zhang et al. proposed in 2022 [159], combines SSr and VVr transfer functions based on opposition learning with ReliefF bootstrapping strategy to achieve good stability between exploration and exploitation and to convert the continuous search space into a binary search space. Additionally, it is clear from the experimental results that the proposed RG-NBEO surpasses other current state-of-the-art metaheuristics when projecting its effectiveness in Feature Selection problem. The Improved Equilibrium Optimizer Regularized Random Vector Functional Link (IEO-RRVFL), which combines the Opposition-Based Learning technique for initial population generation for greater convergence impact, is an updated form of EO that Zhaou et al. proposed in the year 2022 [188]. The experimental findings further demonstrate that the suggested IEO-RRVFL generates high accuracy and stability, demonstrating its effectiveness in comparison to existing algorithms. In order to reduce the segmentation error and enhance the threshold selection approach, Das et al. suggested a new version of EO in the year 2022 [189] known as Opposition Equilibrium Optimizer (OEO). OEO incorporates the Segmentation Score (SS) using Opposition-Based Learning mechanism on EO. The experimental results also show that the suggested OEO works better than previous art-entropy based techniques, demonstrating the effectiveness of the method in the area of image segmentation. Aswini et al. in the year 2022 [190] proposed a revised variant of EO termed as Opposition-based Laplacian Equilibrium Optimizer Algorithm (O-LEO) that incorporates Opposition-Based Learning and Laplacian mechanism to enhance the ability of standard EO. Further, the experimental results clearly highlight that proposed O-LEO has superior performance and proves to be efficient in Healthcare Services. Li et al. in the year 2022 [191] proposed a revised variant of EO termed as Multi-strategy Improved Equilibrium Optimizer (IEO) that uses tent mapping to initialize the algorithm, non-linear parameters to update the position equation for balancing exploration and exploitation of standard EO and Lens Opposition-based Learning (LOBL) to enhance the population diversity. Further, the experimental results clearly highlight that proposed IEO has superior performance when compared with EO, EO, SSA, SCA, BOA, PSO and BA for Numerical Optimization and Engineering problems. Elmanakhly et al. in the year 2021 [167] proposed a revised variant of EO termed as Improved Binary version of the Equilibrium Optimizer Algorithm (IBEO) that employs Opposition Based Learning and Local search algorithm to enhance the population diversity and enhance the exploitation of standard EO. Further, the experimental results clearly highlight that proposed IBEO has superior performance when compared with PSO, GOA, GWO, WOA, DA and ISSA for feature selection problem. Elgamal et al. in the year 2021 [192] proposed a revised variant of EO termed as Improved Equilibrium Optimization Algorithm (IEOA) that employs Elite Opposition-Based Learning (EOBL) and three Local Search approaches such as mutation search, mutation–neighborhood search, and a backup strategy to enhance the diversity in population and for prevention of getting stuck in local optima. Further, the experimental results clearly highlight that proposed IEOA has superior performance when compared with PSO, GA, WOA, GOA, ALO, SMA and BOA for feature selection problem. Fan et al. in the year 2021 [193] proposed a revised variant of EO termed as modified EO (m-EO) that employs opposition-based learning (OBL) and update rules: nonlinear time control strategy, novel population update rules and a chaos-based strategy to enhance the standard EO. Further, the experimental results clearly highlight that proposed m-EO has superior performance when compared with PSO, SCA, PFA, EO, HGSO, OTSA, OBSCA and SOGWO for Engineering Problems. Opposition-based Laplacian Equilibrium Optimizer (OB-L-EO), which combines Laplace distribution and opposition-based learning to improve the performance of standard EO, was proposed by Dinkar et al. in the year 2021 [194]. Also, it is abundantly obvious from the experimental findings that the suggested OB-L-EO performs better for image segmentation than HS, SCA, WOA, MFO, SSO, FASSO, FA, and EO. With the intention to improve the standard EO, Abdel et al. in the year 2021 [152] created the OMOEO-EED-G, a revised version of the EO that integrates the Crowding Distance Approach, Linear and Non-Linear Equations, Exploration–Exploitation Dominance Strategy, Gaussian-based Mutation (G) Strategy, and Opposition-Based Learning. Additionally, experimental results show that the suggested method outperforms when compared to MOEOL, MOEOC, MOEOLog, MOEOT, SMPSO, NS GAII, NSGAIII, PAES2, SMSEMOA, ASMSEMOA, ANSGAII, and ANSGAIII considering several benchmark functions. Naik et al. in the year 2021 [195] proposed a revised variant of EO termed as Context-Sensitive Entropy Dependency based Opposition Equilibrium Optimizer (CSED-OEO) that employs CSED, opposition-based learning and escaping strategy. Further, experimental results clearly highlight that proposed CSED-OEO method provides superior performance when compared with EO, HHO, SFO, WOA, GWO, PSO and DE for multi-thresholding of remote sensing images. Opposition-Based Equilibrium Optimization (OBEO), which uses an opposition-based learning-based update technique to increase the power of regular EO, was proposed by et al. in the year 2021 [196]. Additionally, the experimental findings unmistakably show that the suggested E2O technique outperforms EO, ALO, GWO, WOA, PSOGWO, and GWOCS for parameter estimation in PV models.

4.1.11 Communication Equilibrium Optimizer

An improved version of EO called the Parallel Equilibrium Optimizer (PEO), which Gui et al. introduced in 2021 [197], uses two communication mechanisms to speed up convergence and look for better solutions in the search space. Additionally, the experimental findings demonstrate that the suggested PEO performs better than PSO, GWO, and PPSO for the Capacitated Vehicle Routing Issue (CVRP). Xu et al. in the year 2021 [198] proposed a revised variant of EO termed as compact Equilibrium Optimizer (cEO) algorithm that employs update interval method, parallel communication strategy to enhance the standard EO. Further, the experimental results clearly highlight that proposed cEO has superior performance when compared with PSO, GA, BOA, GSA and GWO for power System networks.

4.1.12 Quantum Equilibrium Optimizer

In 2021 [199], Pan et al. suggested a new version of EO called the Advanced Equilibrium Optimizer (AEO), which uses the multi-population approach, the quantum operator, and the pollination operator to improve the standard EO's global exploration capabilities. Additionally, the experimental findings demonstrate that the proposed AEO outperforms DE, EO, PSO, FPA, and GWO for the Electric Vehicle Routing Problem with Time Windows (EVRPTW).

4.1.13 Other Improved Equilibrium Optimizer

In 2023 [200], Altantawy et al. proposed a new version of the revised EO known as the Minkowski-based Equilibrium Optimizer (MEO), which combines the Sparsification, Pearson correlation, wrapper, and Minkowski-based scheme strategies to improve feature selection, seek the best dimensionality reduction, and improve local minimum avoidance to improve EO performance. The experimental findings also clearly reveal that the proposed MEO outperforms competing classifiers, demonstrating its effectiveness in predicting COVID-19 infection while requiring a small number of blood samples. Vommi et al. in the year 2023 [201] proposed a new variant of revised EO termed as Bi-phase Mutation based Equilibrium Optimizer (BMHEO) that incorporates

Bi-phase Mutation (BM) scheme to enhance the exploitation phase of the EO algorithm and eight S-shaped and V-shaped transfer functions are integrated to convert the solutions to binary form. Further, the experimental result evidently highlights that the proposed BMHEO outperforms other methods namely GA, PSO, GWO, SCA, WOA, HHO, SMA, EO and HEO showcasing its efficacy in medical datasets classifications. The Improved Equilibrium Optimizer (EEO), which combines discretization processing to discretize the standard EO, was proposed by Sun et al. in the year 2022 [202]. Additional evidence of the suggested EEO's effectiveness in Work Shop Scheduling problems comes from the experimental results, which clearly show that it outperforms other cutting-edge metaheuristics like GWO, MVO, DE, and WOA.

The Enhanced Equilibrium Optimizer (EEO), which Eid et al. presented in the year 2022 [203], is a new variation of the improved EO that integrates the technique of optimizing the PV-BES size, position, and power factor to strengthen the current standard EO. The experimental results also clearly reveal that the proposed EEO works better than other current state-of-the-art metaheuristics, such as EO and SCA, demonstrating its effectiveness in Photovoltaic modules and Battery Energy System combination (PV-BES) unit optimization. Aval et al. in the year 2022 [204] proposed a new variant of revised EO termed as Residual Moment-Based Joint Damage Index with Equilibrium Optimizer (RMBJDI-EO) that incorporates Residual Moment-Based Joint Damage Index to enhance standard EO. Further, the experimental result evidently highlights that the proposed RMBJDI-EO outperforms EO and other recent state-of-arts metaheuristics showcasing its efficacy in Joint damage identification. Equilibrium Optimizer—Pattern Search (EO-PS), a novel variation of revised EO that integrates Pattern Search approaches to increase the exploitation capacity further increasing standard EO, was proposed by Rizk et al. in the year 2022 [205]. Additionally, the experimental results clearly reveal that the proposed EO-PS beats EO and other contemporary state-of-the-art metaheuristics, demonstrating its effectiveness in the challenge of optimizing the layout of wind farms. Duan et al. in the year 2022 [206] proposed a new variant of revised EO termed as Hybrid Equilibrium Optimizer based on the Crisscross Strategy (HEOC) that incorporates APBOP, t-distributed stochastic neighbor embedding, crisscross strategy to enhance local search and convergence efficiency of standard EO. Further, the experimental result evidently highlights that the proposed HEOC outperforms ANDE, AC-DPHS and AC-MeanABC and other recent state-of-arts metaheuristics projecting its efficacy in real world optimization problems. Modified Equilibrium Optimizer (MEO), a novel variation of the revised EO that combines several scaling factors on the standard EO to improve its performance, was proposed by Kumar et al. in the year 2022 [207]. Additionally, it is clear from the experimental results that the proposed MEO outperforms EO and other modern, state-of-the-art metaheuristics when predicting its effectiveness in hybrid distributed power systems. Dinh et al. in the year 2022 [208] proposed a revised variant of EO termed as Improved Equilibrium Optimizer (IEO) that works by modifying the equations updating solutions in the standard EO. Further, the experimental results clearly highlight that proposed IEO has superior performance when compared with EO, ABC, SSA, GA, PSO, GA/PSO, SA, HAS, BFOA and BSOA. Houssein et al. in the year 2022 [209] proposed a revised variant of EO termed as Improved version of Equilibrium Optimizer (I-EO) that incorporates Standard operators with the Dimension Learning Hunting (DLH) to enhance the performance of standard EO. Further, the experimental results clearly highlight that proposed I-EO has superior performance when compared with AGDE, GWO, MFO, SCA, HHO, TSA and EO for COVID-19 CT images segmentation. Improved Equilibrium Optimizer (IEO), an updated version of EO that especially focuses on population variety maintenance mechanisms to balance the exploration and exploitation in regular EO, was proposed by Yang et al. in the year 2022 [210]. Additionally, the experimental findings unmistakably show that the proposed IEO outperforms EO, GGSA, HGSA, and RGBSO for the problems of economic dispatch, spacecraft trajectory optimization, and artificial neural network model training. Zhu et al. in the year 2022 [211] proposed a revised variant of EO termed as Improved Equilibrium Optimizer (IEO) that make use of elite guidance and balance probability mechanism to speed up the convergence as well as exploitation ability and also to balance the exploration and exploitation ability of stand EO. Further, the experimental results clearly highlight that proposed IEO has superior performance when compared with EO, SMA, MPA, PFA and WOA for ORPD problems. Improved Equilibrium Optimizer Algorithm (IEO), which leverages function independent of the number of iterations to improve the performance of standard EO, was proposed by Nguyen et al. in the year 2022 [212]. Additionally, it is abundantly obvious from the experimental findings that the suggested IEO outperforms EO, AEO, CSA, TLBO, and ABC for the optimal power flow problem. Ates et al. in the year 2021 [213] proposed a revised variant of EO termed as Enhanced Equilibrium Optimizer (E2O) that employs random coefficients, K feedback gain vector parameters to enhance the standard EO. Further, the experimental results clearly highlight that proposed E2O has superior performance when compared with SMDO and DSO for Hover Flight System. A new version of EO called the Enhanced Equilibrium Optimizer (EEO), which incorporates variable selection probabilities based on its own fitness function to improve the standard EO, was proposed by Sun et al. in the year 2021 [214]. Furthermore, it is abundantly obvious from the experimental data that

Table 3 Various proposed methods under each category of revised EO, along with other details

Revised variant type	Proposed Method	Reference	Year
Dynamic EO	IEO	[132]	2022
	IEO	[133]	2022
	UEO	[134]	2021
Adaptive EO	SQEOABC	[135]	2023
	self-EO	[136]	2022
	DEO	[137]	2022
	HEOCAE	[138]	2022
	AEO	[139]	2022
	AIEOU	[140]	2021
	IEO	[149]	2021
	AEO	[141]	2020
Fuzzy EO	HEOCAE	[138]	2022
	HFEO	[142]	2022
	MEO-IT2FPID	[143]	2021
Chaotic EO	NMIEO	[144]	2022
	IEO	[132]	2022
	IEO	[133]	2022
	DIEO	[145]	2022
	CEO	[146]	2022
	CS-CEOA	[147]	2021
	E^2O	[148]	2021
	IEO	[149]	2021
	CEOA	[150]	2020
Gaussian EO	ELM-MEO	[151]	2022
	MOEO-EED-G	[152]	2021
	OMOEO-EED-G	[152]	2021
	MHEO	[153]	2021
	m-EO	[154]	2020
Binary EO	BiEO	[155]	2022
	RBEO-LS	[156]	2022
	BIMEO	[157]	2022
	AV-BMEO	[158]	2022
	RG-NBEO	[159]	2022
	BMEO	[160]	2022
	NDEOA	[161]	2022
	BEOA	[162]	2022
	BEO	[163]	2022
	DEOA-CRM	[164]	2022
	DEOSA	[165]	2022
	BEOA	[166]	2022
	IBEO	[167]	2021
	BEO	[168]	2021
	BEO-S & BEO-V	[169]	2020
	BEO-T	[169]	2020

Table 3 (continued)

Revised variant type	Proposed Method	Reference	Year
Levy-flight EO	LWMEO	[170]	2022
	BIMEO	[157]	2022
	MEO	[171]	2022
	LEO	[172]	2022
	IEOLF	[173]	2022
	LSFEO	[174]	2021
	MHEO	[153]	2021
	Levy_EOA	[175]	2020
Multi-objective EO	IMOEO	[176]	2022
	MOEOT	[177]	2022
	CMOEO	[178]	2022
	R_2HMEOA	[179]	2022
	MOEO	[180]	2022
	CMEO	[181]	2021
	MOEO-EED-G	[152]	2021
	OMOEO-EED-G	[152]	2021
	MOEO	[152]	2021
	MOEOS	[152]	2021
	MOEO-EED	[152]	2021
	MEOA	[182]	2021
	DMOEOA	[183]	2020
Disturbance-based EO	DIEO	[184]	2023
	DIEO	[145]	2022
	IILEO	[185]	2021
Opposition-based learning EO	AEO	[186]	2023
	IS-EO	[187]	2022
	AV-BMEO	[158]	2022
	RG-NBEO	[159]	2022
	IEO-RRVFL	[188]	2022
	OEO	[189]	2022
	O-LEO	[190]	2022
	IEO	[191]	2022
	IBEO	[167]	2021
	IEOA	[192]	2021
	m-EO	[193]	2021
	OB-L-EO	[194]	2021
	OMOEO-EED-G	[152]	2021
	CSED-OEO	[195]	2021
	OBEO	[196]	2021

Table 3 (continued)

Revised variant type	Proposed Method	Reference	Year
Improved EO	MEO	[200]	2022
	BMHEO	[201]	2022
	EEO	[202]	2022
	EEO	[203]	2022
	RMBJDI-EO	[204]	2022
	EO-PS	[205]	2022
	HEOC	[206]	2022
	MEO	[207]	2022
	IEO	[208]	2022
	I-EO	[209]	2022
	IEO	[210]	2022
	IEO	[211]	2022
	IEO	[212]	2022
	E2O	[213]	2021
	EEO	[214]	2021
	GLEO	[215]	2021
	IEO	[216]	2021
	RW-EOA	[217]	2020
	IEO	[218]	2020
Communication EO	PEO	[197]	2021
	CEO	[198]	2021
Quantum EO	AEO	[199]	2021

for optimal control designs, proposed EEO performs better than EO and GA. Global Learning Equilibrium Optimization (GLEO), which integrates a general learning method to avoid the local optima in regular EO and improve the exploration mechanism, was proposed by Too et al. in the year 2021 [215]. Also, it is abundantly obvious from the experimental findings that the suggested GLEO performs better than EO, BOA, GWO, PSO, and RF when it comes to classifying medical data. Wang et al. in the year 2021 [216] proposed a revised variant of EO termed as Improved Equilibrium Optimizer (IEO) that incorporates back propagation Neural Network to predict more output data of PV cell. Further, the experimental results clearly highlight that proposed IEO has superior performance when compared with ABC, BSA, GWO, MFO, PSO, WOA and EO for Photovoltaic cell parameter estimation. Zhao et al. in the year 2020 [217] proposed a revised variant of EO termed as Random Walk Equilibrium Optimizer Algorithm (RW-EOA) that employs random walk with Cauchy distribution to enhance the performance of standard EO. Further, experimental results clearly highlight that among the proposed RW-EOA provides superior performance when compared with original EO for optimization of classical benchmark functions. Abdel et al. in the year 2020 [218] proposed a revised variant of EO termed as Improved Equilibrium Optimizer (IEO) that employs Linear Reduction Diversity (LRD) and Local Minima Elimination method (MEM) to boost the standard EO. Further, experimental results clearly highlight that among the proposed IEO provides superior performance when compared with CPMPSO, MADE, ITLBO and MLBSA for multilevel thresholding.

The various methods proposed under each category of revised EO, along with other details, are tabulated in Table 3. The improvement strategies or methods along with other details, of the revised variants of EO proposed by various researchers that have been surveyed in this article, are tabulated in Table 4. Also, the full form of each acronym used in Table 4 is tabulated in Table 7.

4.2 Hybridized variants of Equilibrium Optimizer (EO)

One of the prominent ways to improve the ability of any nature-inspire metaheuristic algorithm is by means of hybridization. Hybridization not only enables the balancing exploration–exploitation ability of algorithm, but it also enhances their ability to become acquainted with specific information in a given situation. This section discusses the hybridized variants of EO as depicted in Fig. 14, and the year-wise depiction of the research articles discussing the same is shown in Fig. 15.

A number of metaheuristic algorithms have been hybridized with EO, proposing and introducing new hybridized variants of EO. A description of the research article dealing with the aforementioned method proposal is described below and shown in Fig. 16.

4.2.1 Hybridization with Artificial Bee Colony (ABC)

The Self-Adaptive Quantum Equilibrium Optimizer with Artificial Bee Colony (SQEOABC) is a new version of the revised and hybridized EO that Zhong et al. proposed in 2023 [135]. It uses the updating mechanism of the ABC to find the best solution and incorporates quantum theory and self-adaptive mechanisms into the EO's updating rule to improve convergence. The experimental results further reveal that the proposed SQEOABC performs better than existing state-of-the-art metaheuristics such as PSO, CMAES, GWO, SSA, HHO, SMA, WSO, TLSMA, DDSRPSO, EESHHO, and LSHADE-cnEpSin for the COVID-19 feature selection problem.

4.2.2 Hybridization with Teaching–Learning-Based Optimization (TLBO)

Hybrid Teaching Learning Based Optimization-Equilibrium Optimization (TLBO-EO), which combines the high exploration ability of TLBO with the high exploitation ability of EO, was proposed by Sayed et al. in the year 2023 [219]. The experimental result evidently highlights that, for estimating PV cell performance, the proposed TLBO-EO beats existing cutting-edge metaheuristics like PSO and PSO-CFA. The Modified Equilibrium Optimizer using Teaching–Learning-based Optimization and Opposition-Based Learning (OTLEO) is a hybridized EO that Wang et al. proposed in 2022 [220]. It combines EO with TLBO and OBL to preserve the diversity of the solutions, expand the search space, improve exploration and exploitation skills, and further avoid local optima. Additionally, it is clear from the experimental results that the proposed OTLEO outperforms EO and m-EO when tested against a variety of traditional benchmark functions.

4.2.3 Hybridization with Whale Optimization Algorithm (WOA)

In the year 2022 [170], Liu et al. proposed a new variant of revised and hybridized EO called the Levy Whale Optimization Mutation Equilibrium Optimizer (LWMEO), which combines the random walk strategy based on Lévy flight, the spiral encirclement mechanism of WOA, and the adaptive proportional mutation strategy to increase search range and exploration ability, exploitation ability, and speed up the convergence speed of the standard EO. The experimental results also clearly show that the proposed LWMEO performs better than existing state-of-the-art metaheuristics including EO, AEO, IEO, SSA, MSSA, and JADE, demonstrating its effectiveness in many engineering fields. Hybrid multi-objective Equilibrium Optimizer and Whale Optimization Algorithm (R2-HMEWO), which executes hybridization in the form of structure and operators, was proposed by Tahernezhad et al. in the year 2022 [221]. Furthermore, the experimental outcome clearly shows that for benchmark test issues, the proposed R2-HMEWO beats existing state-of-the-art metaheuristics like NSGA-III, NSGA-II, MOEA/D, MOMBI-II, MOEA/IGD-NS, and dMOPSO. Equilibrium Whale Optimization Algorithm (EWOA), which combines the weight balance technique of EO with the encircling and net-bubble attacking mechanisms of WOA, was proposed by Tan et al. in the year 2022 [222]. Additionally, it is clear from the experimental results that the proposed EWOA performs better than DMOA, POA, DOA, AOA, EO, and WOA for a number of benchmark test problems.

4.2.4 Hybridization with Adaptive Fuzzy based Atom Search Optimizer (AFASO) and Adaptive Rain Optimization (ARO)

Hybrid Equilibrium Optimizer with Capsule Auto Encoder (HEOCAE), which incorporates Skull stripping, Normalized Linear Smoothing and Median Joint (NLSMJ) filtering, Adaptive Fuzzy based Atom Search Optimizer, Adaptive rain optimization, and capsule auto encoder at different stages to enhance the standard EO, was proposed by Ansingkar et al. in the year 2022 [138]. The experimental results also clearly reveal that the proposed HEOCAE works better than EO and other contemporary state-of-the-art metaheuristics, demonstrating its effectiveness in the Multi class Alzheimer detection problem.

4.2.5 Hybridization with Genetic Algorithm (GA)

In 2022 [223], Heidari et al. introduced the Genetic Algorithm and Equilibrium Optimizer (GA-EO), a hybridized EO

Table 4 Summary of the different research work carried out using revised variants of EO algorithm

SI	Proposed method	Year	Strategy/operator included/method/factors incorporated	Problems	Citation	References	Publisher
1	Disturbance inspired equilibrium optimizer (DIEO)	2023	Disturbance-based hybrid initialization strategy	Engineering design problems	0	[184]	Elsevier
2	Self-adaptive quantum equilibrium optimizer with artificial bee colony (SQEOABC)	2023	Self-adaptive and quantum theory	Feature selection (COVID-19)	0	[135]	Elsevier
3	Ameliorated equilibrium optimizer (AEO)	2023	Opposition-based learning, centroid opposition-based learning and self-learning strategies	Path planning of the unmanned ground vehicle (UGV)	0	[186]	Elsevier
4	Minkowski-based equilibrium optimizer (MEO)	2023	Sparsification, Pearson correlation, wrapper and Minkowski-based scheme	COVID-19 diagnosis	0	[200]	Elsevier
5	Bi-phase mutation based equilibrium optimizer (BMHEO)	2023	Bi-phase mutation scheme, S-shaped and V-shaped transfer functions	Medical dataset classification	1	[201]	Elsevier
6	Self-adaptive equilibrium optimizer (self-EO)	2022	Exploration/exploitation balancing, Self-adaptive of control parameters and Population reduction	Global, combinatorial, engineering, and multi-objective problems	16	[136]	Elsevier
7	Enhanced equilibrium optimizer (EEO)	2022	Discretization processing	job shop scheduling problem	10	[202]	Springer
8	Binary equilibrium optimizer (BiEO)	2022	V-shape transfer function	Optimal control problems (building and construction industry)	0	[155]	Elsevier
9	ReliefF binary equilibrium optimizer with local search (RBEO-LS)	2022	ReliefF filter method and the binary EO with local search strategy	Feature selection	12	[156]	Elsevier
10	Normalized Mutual Information-based equilibrium optimizer (NMIEO)	2022	Local search strategy and chaotic maps	Feature selection	4	[144]	Elsevier
11	Extreme learning machine modified equilibrium optimizer (ELM-MEO)	2022	Gaussian mutation with an exploratory search mechanism	Soil compression index prediction (roadways, railways and airport runways)	19	[151]	Elsevier
12	Levy whale optimization mutation equilibrium optimizer (LWMEO)	2022	Random walk strategy based on Lévy flight, WOA's spiral encirclement mechanism and adaptive proportional mutation strategy	Engineering problems	5	[170]	Elsevier
13	Equilibrium optimizer with divided population (DEO)	2022	Adaptive population division strategy comprising of beta distribution, distance factor and exponential term	Feature selection	0	[137]	Elsevier
14	Improved multi-objective equilibrium optimizer (IMOEO)	2022	Optimal PV energy utilization strategy and hybrid opposite learning strategy and the spiral operator	Optimal scheduling of residential houses	1	[176]	Elsevier
15	Binary improved equilibrium optimizer (BIMEO)	2022	mRMR, Wrapper feature selection approach, Entropy-based and Levy-flight operators	Feature selection	4	[157]	Elsevier
16	Information-utilization strengthened equilibrium optimizer (IS-EO)	2022	Information sharing and guiding, global-best opposition learning and differential mutation strategy	Engineering design problems	1	[187]	Springer

Table 4 (continued)

SI	Proposed method	Year	Strategy/operator included/method/factors incorporated	Problems	Citation	References	Publisher
17	Enhanced equilibrium optimizer (EEO)	2022	Optimization of PV-BES size, location, and power factor	Optimization of photovoltaic modules and battery energy system combination (PV-BES) units	1	[203]	Springer
18	AV- Binary modified equilibrium optimizer (AV-BMEO)	2022	AV-shape transfer function, opposition-based learning, k-nearest neighbor classifier	Feature selection	8	[158]	Elsevier
19	Modified equilibrium optimizer (MEO)	2022	Iterative cosine operator (ICO), Levy flight	Engineering optimization problems	6	[171]	Wiley
20	Residual moment-based joint damage index with equilibrium optimizer (RMBJDI-EO)	2022	Residual moment-based joint damage index	Joint damage identification	5	[204]	World Scientific
21	Levy equilibrium optimizer (LEO)	2022	Levy flight update strategy	DNA storage	0	[172]	Plos
22	Equilibrium optimizer -pattern search (EO-PS)	2022	Pattern search	Wind farm layout optimization problem	3	[205]	Elsevier
23	Hybrid equilibrium optimizer with capsule auto encoder (HEOCAE)	2022	Skull stripping, and normalized linear smoothing and median joint (NLSMJ) filtering, adaptive fuzzy based atom search optimizer, adaptive rain optimization, capsule auto encoder	Multi class Alzheimer detection	3	[138]	Springer
24	Multi-objective equilibrium optimization technique (MOEOT)	2022	Pareto optimal front	Photovoltaic modules (Radial distribution systems)	1	[177]	Elsevier
25	Hybrid equilibrium optimizer based on the crisscross strategy (HEOC)	2022	Affinity propagation based on optimization of preference (APBOP), t-distributed stochastic neighbor embedding, crisscross strategy	Real world optimization problems	0	[206]	Elsevier
26	ReliefF-guided novel binary equilibrium optimizer (RG-NBEO)	2022	Transfer functions (SSr and VVr) based on the concept of opposition learning, ReliefF bootstrapping strategy	Feature selection	0	[159]	Springer
27	Modified equilibrium optimization (MEO)	2022	Scaling factors	Hybrid distributed power systems	4	[207]	Springer
28	Improved equilibrium optimization based on levy flight (IEOLF)	2022	Levy flight strategy	Feature selection	4	[173]	Springer
29	Multi-objective equilibrium optimizer algorithm integrated Competition Mechanism (CMOEO)	2022	Competition mechanism, differential evolution	Photovoltaic energy storage system	0	[178]	Springer
30	Binary Modified equilibrium optimizer (BMEO)	2022	Band selection, V-shape transfer function	Hyperspectral image classification	0	[160]	SPIE digital Library
31	Novel Discrete Equilibrium Optimizer Algorithm (NDEOA)	2022	Discrete encoding, Discrete operators	Classification Rule Generation	0	[161]	Ios Press

Table 4 (continued)

SI	Proposed method	Year	Strategy/operator included/method/factors incorporated	Problems	Citation	References	Publisher
32	Improved Equilibrium Optimizer Regularized Random Vector Functional Link (IEO-RRVFL)	2022	Opposition-Based Learning	Color Constancy	3	[188]	Optica
33	Opposition Equilibrium Optimizer (OEO)	2022	Segmentation Score (SS), Segmentation Error Minimization (SEM), OBL	Image Segmentation	0	[189]	World Scientific
34	Improved Equilibrium Optimizer (IEO)	2022	Dynamic sine and cosine factors and Chaotic initialization	Power Systems	0	[132]	IEEE
35	Opposition-based Laplacian Equilibrium Optimizer Algorithm (O-LEO)	2022	Opposition-Based Learning	Cloud-based Healthcare Services Paradigm (HCS)	23	[190]	Wiley
36	Binary version of the Equilibrium Optimization Algorithm (BEOA)	2022	Binary encoding	Domination metric dimension problem	0	[162]	Hindawi
37	Improved Equilibrium Optimizer (IEO)	2022	Modified Equation updating solution	Distribution Systems	0	[208]	Hindawi
38	Binary version of Equilibrium Optimizer (BEO)	2022	Modified equations of Equilibrium concentration and position updation	Feature Selection	0	[163]	Taiwan Ubiquitous Information
39	Hybrid Fuzzy Equilibrium Optimizer (HFEO)	2022	Fuzzy based fitness function	Estimation of size and location of Distributed Generators	1	[142]	Elsevier
40	R_2 index hybrid multi-objective Equilibrium Optimization Algorithm (R_2HMEOA)	2022	R_2 index and elite archiving strategy	Mine Ventilation System	1	[179]	Elsevier
41	Improved version of Equilibrium Optimizer (I-EO)	2022	Standard operators with the Dimension Learning Hunting (DLH)	COVID-19 CT images segmentation	22	[209]	Elsevier
42	Classification Rule Mining using a Discrete Equilibrium Optimization Algorithm (DEOA-CRM)	2022	Sequential Covering Strategy for Classification Rule Mining, Discrete operators	Classification Rule Generation	3	[164]	Elsevier
43	Discrete Equilibrium Optimizer Simulated Annealing (DEOSA)	2022	U-shaped transfer function, SA for local search procedure	Feature Selection	3	[165]	Elsevier
44	Multi-strategy Improved Equilibrium Optimizer (IEO)	2022	Tent mapping, non-linear time parameter, Lens Opposition-based Learning (LOBL)	Numerical Optimization and Engineering problems	0	[191]	Plos
45	Improved Equilibrium Optimizer (IEO)	2022	Population diversity maintenance	Economic dispatch, spacecraft trajectory optimization problem and artificial neural network model training problem	0	[210]	MDPI
46	Improved Equilibrium Optimizer (IEO)	2022	Chaotic Equilibrium Pool, nonlinear dynamic generation mechanism and Golden Sine Strategy	Optimal Power Flow Problem	2	[133]	MDPI
47	Disturbance-Inspired Equilibrium Optimizer (DIEO)	2022	Good nodes set theory, chaotic sequence	Hydrogeological parameters identification Problems	1	[145]	MDPI
48	Improved Equilibrium Optimizer (IEO)	2022	Elite guidance and balance probability strategy	Optimal Reactive Power Dispatch (ORPD) problem	1	[211]	Pre-Print

Table 4 (continued)

SI	Proposed method	Year	Strategy/operator included/method/factors incorporated	Problems	Citation	References	Publisher
49	Binary Equilibrium Optimization Algorithm (BEOA)	2022	Rule Representation, Classification rule extraction	Sentiment Analysis	1	[166]	Springer
50	Chaotic Equilibrium Optimizer Algorithm (CEO)	2022	8 different S-shaped and V-shaped transfer functions	Feature Selection and Global Optimization Problems	13	[146]	Springer
51	Multi-Objective Equilibrium Optimizer Algorithm (MOEO)	2022	Crowding distance mechanism, non-dominated sorting strategy and an archive with update function	Multi-Objective Optimization Problems	15	[180]	Nan
52	Adaptive Equilibrium Optimizer (AEO)	2022	Non-Entropic objective function, reinforcement threshold selection process, adaptive decision-making	Multilevel Optimal Threshold Selection	0	[139]	IUST
53	Improved Equilibrium Optimizer Algorithm (IEO)	2022	Function independent of number of iterations	Optimal Power Flow Problem	0	[212]	Hindawi
54	United Equilibrium Optimizer (UEO)	2021	United parameters into equilibrium pool, Dynamic parameters	Multi-Modal Image Registration	1	[134]	Elsevier
55	Parallel Equilibrium Optimizer (PEO)	2021	Communication strategies	Capacitated Vehicle Routing Problem (CVRP)	12	[197]	Tech Science Press
56	Enhanced Equilibrium Optimizer (E2O)	2021	Random coefficients, K feedback gain vector parameters	Hover Flight System	1	[213]	ASME
57	Enhanced Equilibrium Optimizer (EEO)	2021	Varying selection probabilities	Optimal Control Designs	0	[214]	IET
58	Automata-based Improved Equilibrium Optimizer with U-shaped transfer function (AIEOU)	2021	U-shaped transfer function, learning based Automata, Adaptive β Hill Climbing (AβHC)	Feature Selection	23	[140]	Elsevier
59	Advanced Equilibrium Optimizer (AEO)	2021	Multi-population method, quantum operator and pollination operator	Electric Vehicle Routing Problem with Time Windows (EVRPTW)	5	[199]	Taiwan Ubiquitous Information
60	Compact Equilibrium Optimizer (CEO)	2021	Update interval method, Parallel communication strategy	Power System Network	9	[198]	Taiwan Ubiquitous Information
61	Constrained Multiobjective Equilibrium Optimizer Algorithm (CMEO)	2021	Minimization of Pareto border, Repair algorithm	Combined Economic Emission Dispatch Problem (CEEDP)	13	[181]	Hindawi
62	Interswarm Interactive Learning Strategy Equilibrium Optimizer (IILEO)	2021	Interswarm Interactive Learning, global optimal disturbance strategy	UAV path planning problem	1	[185]	Taylor and Francis
63	Improved Binary version of the Equilibrium Optimizer Algorithm (IBEO)	2021	Opposition Based Learning, Local search algorithm, Wrapper approaches,	Feature Selection	12	[167]	IEEE
64	Improved Equilibrium Optimization Algorithm (IEOA)	2021	Opposition-Based Learning and New Local Search Strategy	Feature Selection	24	[192]	MDPI
65	General Learning Equilibrium Optimizer (GLEO)	2021	Wrapper feature selection method, general learning strategy	Biological Data Classification	32	[215]	Taylor and Francis
66	Binary version of Equilibrium Optimization (BEO)	2021	Eight transfer functions including V-Shaped and S-Shaped, penalty function, Repair Algorithm (RA)	0–1 Knapsack Problem	32	[168]	Elsevier

Table 4 (continued)

SI	Proposed method	Year	Strategy/operator included/method/factors incorporated	Problems	Citation	References	Publisher
67	Improved Equilibrium Optimizer (IEO)	2021	Back propagation neural network	Photovoltaic cell parameter estimation	47	[216]	Elsevier
68	modified EO (m-EO)	2021	OBL and update rules: nonlinear time control strategy, novel population update rules and a chaos-based strategy	Real Engineering Problems	28	[193]	Elsevier
69	Opposition-based Laplacian Equilibrium Optimizer (OB-L-EO)	2021	Opposition based learning,	Image Segmentation	34	[194]	Elsevier
70	Multi-Objective Equilibrium Optimizer (MOEO) Multi-Objective Equilibrium Optimizer improved using Sine Function (MOEOS) Multi-Objective Equilibrium Optimizer with Exploration–Exploitation Dominance strategy (MOEO-EED) Multi-Objective Equilibrium Optimizer with Exploration–Exploitation Dominance strategy-Gaussian-based mutation (G) strategy (MOEO-EED-G) Opposition-Based Multi-Objective Equilibrium Optimizer with Exploration–Exploitation Dominance strategy- Gaussian-based mutation (G) strategy (OMOEO-EED-G)	2021	Crowding distance approach, Linear and non-linear equations, Exploration–Exploitation Dominance strategy, Gaussian-based mutation (G) strategy, Opposition-Based Learning	Multi-objective Optimization problems	20	[152]	Elsevier
71	Multi-objective Equilibrium Optimizer Algorithm (MEOA)	2021	Improvement-Based Reference Points Method (IBRPM)	Multi-objective Optimization problems	30	[182]	Elsevier
72	Context-Sensitive Entropy Dependency based Opposition Equilibrium Optimizer (CSED-OEO)	2021	Opposition based learning and escaping strategy	Multilevel thresholding of remote sensing images	12	[195]	Elsevier
73	Modified Equilibrium Optimization Algorithm-based Interval Type-2 Fuzzy Proportional Integral Derivative Controller (MEO-IT2FPID)	2021	Interval Type-2 Fuzzy logic Proportional Integral Derivative controller	Frequency control of an AC microgrid	4	[143]	Springer
74	Levy Spiral Flight Equilibrium Optimizer (LSFEO)	2021	Levy Flight distribution, Spiral motion of the particles	Optimal Power Flow (OPF) problem	9	[174]	IEEE
75	Chaotic Search based Constrained Equilibrium Optimizer Algorithm (CS-CEOA)	2021	Exhaustive local search, chaos-based search algorithm	Non-Linear Programming and Petrochemical application	12	[147]	MDPI
76	Enhanced Equilibrium Optimization Algorithm (E^2O)	2021	Fractional Order Chaotic (FOC) system models, controller parameter optimization,	Engineering Problems	13	[148]	Springer

Table 4 (continued)

SI	Proposed method	Year	Strategy/operator included/method/factors incorporated	Problems	Citation	References	Publisher
77	Opposition-based Equilibrium Optimization (OBEO)	2021	Opposition based learning strategy	Parameter Estimation in PV models	13	[196]	Springer
78	Improved Equilibrium Optimization (IEO)	2021	Chaotic mechanism, adaptive weights and adaptive convergence factors	Neural Network	4	[149]	MDPI
79	Multiple Population Hybrid Equilibrium Optimizer (MHEO)	2021	Gaussian distribution estimation, Lévy flight and inferior solution shift strategy	Unmanned Aerial Vehicle (UAV) path planning	18	[153]	MDPI
80	Disruption-based Multi-Objective Equilibrium Optimization Algorithm (DMOEOA)	2020	Layered Disruption Method (LDM), Disruption operator	Structural Optimization	7	[183]	Hindawi
81	Binary Equilibrium Optimizer Algorithm based on S and V Transfer function (BEO-S and BEO-V) Binary Equilibrium Optimizer Algorithm based on Target (BEO-T)	2020	S-Shaped and V-Shaped Transfer Functions, Target dimension	Feature Selection	48	[169]	IEEE
82	Random Walk Equilibrium Optimizer Algorithm (RW-EOA)	2020	Random walk, Cauchy distribution	Optimization of classical benchmark functions	6	[217]	IEEE
83	Chaotic Equilibrium Optimizer Algorithm (CEOA)	2020	Tent map, chaos method	Optimization of classical benchmark functions	4	[150]	IEEE
84	Improved Equilibrium Optimization Algorithm with Levy Flight (Levy_EOA)	2020	Levy Flight	Unimodal, multimodal and the bottom flat-like benchmark functions	4	[175]	IEEE
85	modified Equilibrium Optimizer (m-EO)	2020	Gaussian mutation	Numerical Optimization	63	[154]	Elsevier
86	Adaptive Equilibrium Optimizer (AEO)	2020	Interdependence based technique, adaptive decision making	Multilevel Thresholding	38	[141]	Elsevier
87	Improved Equilibrium Optimizer (IEO)	2020	Linear Reduction Diversity (LRD) and Local Minima Elimination method (MEM)	Solar Photovoltaic parameter estimation	72	[218]	Elsevier

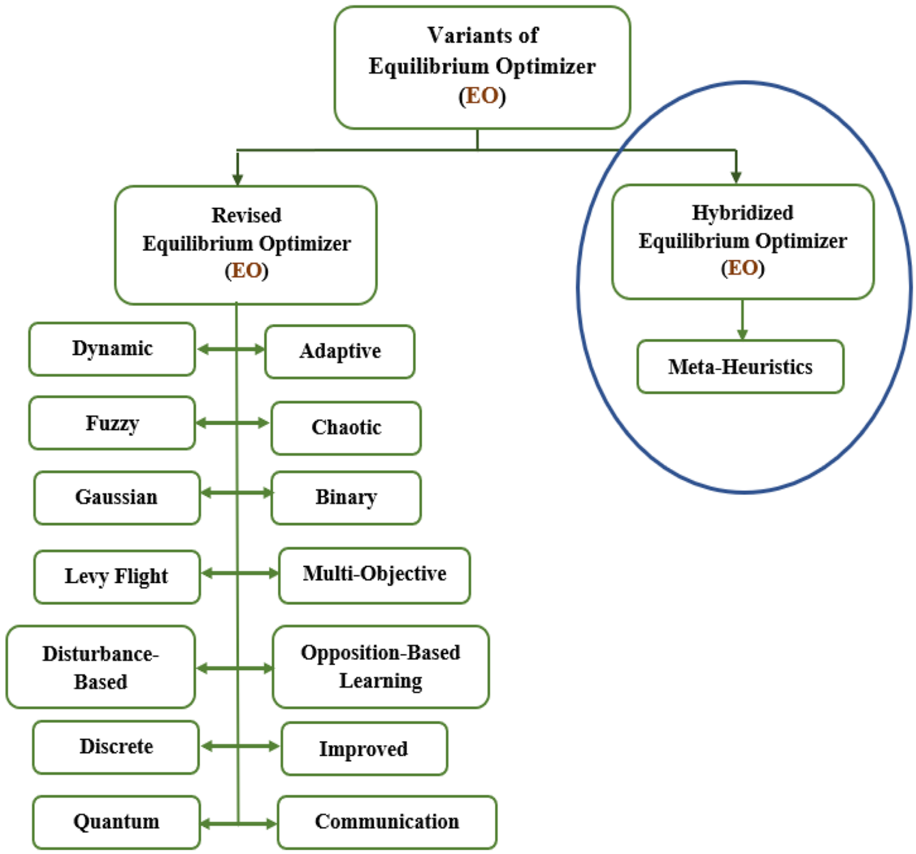


Fig. 14 Hybridized variants of EO

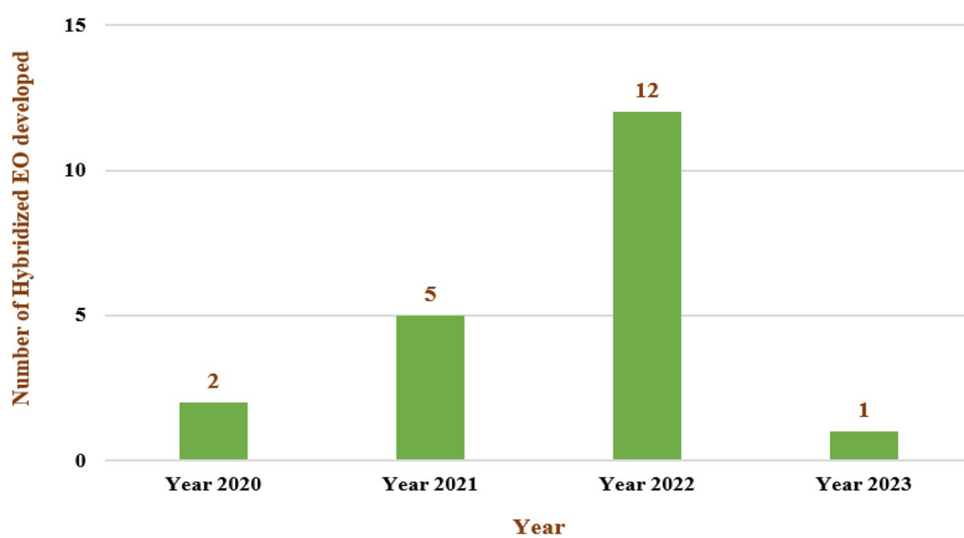


Fig. 15 Year-wise depiction of the various research article based on hybridized variants of EO (As per the survey)

that combines EO and GA for the aim of choosing the path between the base station and cluster heads. Additionally, it is clear from the experimental results that the proposed GA-EO outperforms existing state-of-the-art metaheuristics for clustering and routing in WSN. In the year 2022 [224], Hemeida et al. presented a hybridized EO known as Genetic Algorithm-Equilibrium Optimization (GAEO), which combines the exploitative capabilities of EO with the explorative capabilities of GA to create a more effective technique. Also, the experimental results clearly show that for the reactive

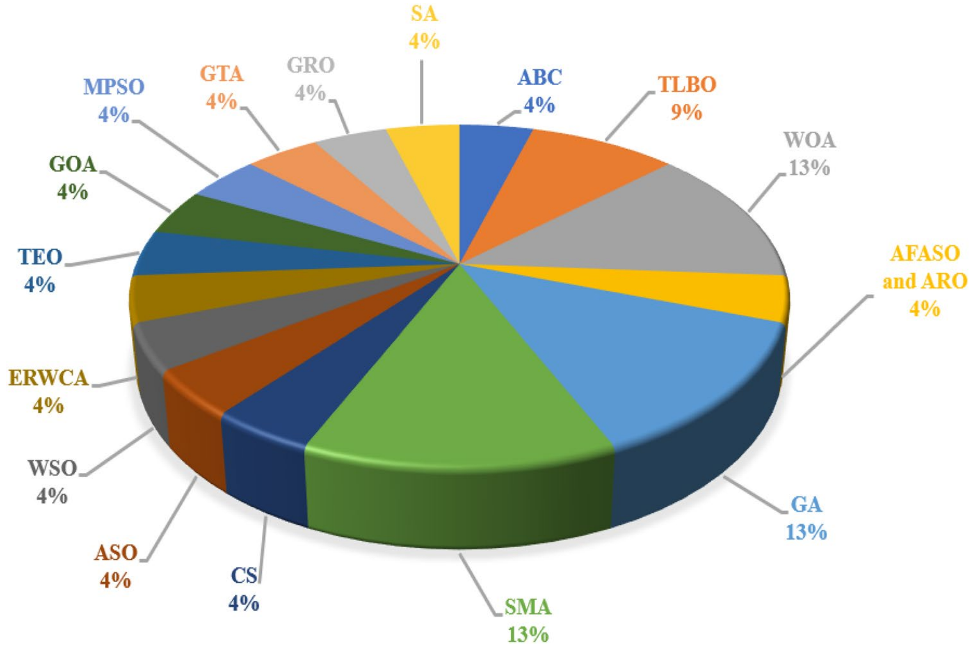


Fig. 16 Proportions of research articles addressing the various meta-heuristics algorithms hybridized with EO (As per the survey)

power management problem, the suggested GAEO performs better than SCA, CBA, and ISSA. Hybrid Genetic Algorithm Equilibrium Optimizer (GAEO), which combines EO and GA to generate a switch between exploration and exploitation, was proposed by Bakry et al. in the year 2022 [225]. Furthermore, the experimental data clearly shows that for distribution networks, the proposed GAEO outperforms GA, GASBO, SBO, TLBO, PSO, GA/PSO, BFOA, SA, QOTLBO, and IA.

4.2.6 Hybridization with Slime Mould Algorithm (SMA)

Equilibrium Optimizer Slime Mould Algorithm (EOSMA), a hybridized EO that includes the exploration and exploitation capabilities of SMA to improve the algorithm, was proposed by Yin et al. in the year 2022 [226]. Additionally, the experimental result clearly shows that the proposed EOSMA outperforms SMA, EO, MPA, IGWO, AGPSO, and MTDE employed for various cutting-edge metaheuristics for engineering design issues. A hybridized EO called the Equilibrium Optimizer Slime Mould Algorithm (EOSMA) and a Multi-Objective EOSMA (MOEOSMA) were proposed by Yin et al. in the year 2022 [227]. These algorithms use the concentration update operator of the EO to direct the SMA search mechanism, a greedy strategy to speed up convergence and escape from local optima, and a random difference mutation operator. Furthermore, the experimental data clearly shows that for inverse kinematics of the 7 DOF robotic manipulator, the proposed approaches perform better than MOMPA, MOGWO, MOALO, and MOSMA. Equilibrium Optimizer into Slime Mould Algorithm (EOSMA), which essentially combines SMA with EO and Centroid Opposition-based Computation (COBC) strategy, was proposed by Wei et al. in the year 2022 [228] in order to strengthen exploration and exploitation, accelerate convergence, and prevent stagnation. Additionally, the experimental results clearly show that for the Work Shop Scheduling problem, the suggested EOSMA outperforms EO, MPA, AO, BES, and SMA.

4.2.7 Hybridization with Cuckoo Search (CS)

Equilibrium-Cuckoo Search Optimizer (ECSO), a hybridized EO that uses CS and EO to reduce Differential Exponential Entropy (DEE), was proposed by Swain et al. in the year 2022 [229]. Furthermore, the experimental results clearly show that for multilevel threshold selection in colour satellite images, the proposed ECSO outperforms other state-of-the-art metaheuristics such as CSA and EO.

4.2.8 Hybridization with Atom Search Optimization (ASO)

In 2022 [230], Chattopadhyay et al. introduced the Clustering-based Equilibrium Optimizer and Atom Search Optimization algorithm (CEOAS), a hybridized EO that uses both EO and ASO to help reduce feature dimensions and hence increase classification accuracy. Additionally, it is clear from the experimental results that the proposed CEOAS outperforms other state-of-the-art metaheuristics for speech emotion identification.

4.2.9 Hybridization with White Shark Optimizer (WSO)

White Shark Equilibrium Optimizer (WSEO), a hybridized EO proposed by Makhadmeh et al. in the year 2022 [231], uses the searching components of WSO and EO to improve the performance of the WSO search agents in order to find the best schedules and maintain an ideal balance between exploration and exploitation in order to prevent stagnation in local optima. Furthermore, the experimental results clearly show that for power scheduling issues, the suggested WSEO outperforms DE, DMOA, GWO, SSA, and WSO.

4.2.10 Hybridization with Evaporation Rate Water Cycle Algorithm (ERWCA)

Equilibrium Optimizer- Evaporation Rate Water Cycle Algorithm (EO-ERWCA), a hybridized EO that uses EO over one subpopulation and ERWCA over another subpopulation, was proposed by Calasan et al. in the year 2022 [232]. Also, the experimental results clearly show that the suggested EO-ERWCA performs better for PID controller in AVR systems than CS, WOA, and YSGA.

4.2.11 Hybridization with Thermal Exchange Optimization (TEO)

High Equilibrium Optimizer (HEO), which combines EO and TEO to create a highly balanced optimizer without altering the memory mode and guiding strategy of the standard EO, was proposed by Jia et al. in the year 2021 [233]. The experimental results also clearly show that the proposed HEO performs better than existing state-of-the-art metaheuristics including EO, TEO, GSA, MVO, SHO, GWO, and SCA, demonstrating its effectiveness in a variety of engineering design domains.

4.2.12 Hybridization with Grasshopper Optimization Algorithm (GOA)

Hybrid Equilibrium Optimizer (HEO), a novel variation of hybridized EO that employs the benefits of GOA to improve the optimization capability of regular EO, was proposed by Qi et al. in the year 2021 [234]. Additionally, the experimental results clearly reveal that the proposed HEO performs better than other state-of-the-art metaheuristics including EOA, CSA, FPA, PSO, and BA, demonstrating its effectiveness in the multi-level picture segmentation domain.

Table 5 Various meta-heuristic algorithms hybridized with EO

Meat-Heuristic algorithm hybridized with EO	Proposed method	References	Year
Artificial bee colony (ABC)	SQEOABC	[135]	2023
Teaching–learning-based optimization (TLBO)	TLBO-EO	[219]	2023
	OTLEO	[220]	2022
Whale optimization algorithm (WOA)	LWMEO	[170]	2022
	R2-HMEWO	[221]	2022
	EWOA	[222]	2022
Adaptive fuzzy based atom search optimizer (AFASO) and adaptive rain optimization (ARO)	HEOCAE	[138]	2022
Genetic algorithm (GA)	GA-EO	[223]	2022
	GAEO	[224]	2022
	GAEO	[225]	2022
Slime mould algorithm (SMA)	EOSMA	[226]	2022
	MOEOSMA	[227]	2022
	EOSMA	[228]	2022
Cuckoo search (CS)	ECSO	[229]	2022
Atom search optimization (ASO)	CEOAS	[230]	2022
White shark optimizer (WSO)	WSEO	[231]	2022
Evaporation rate water cycle algorithm (ERWCA)	EO–ERWCA	[232]	2021
Thermal exchange optimization (TEO)	HEO	[233]	2021
Grasshopper optimization algorithm (GOA)	HEO	[234]	2021
Modified particle swarm optimization (MPSO)	MPSO-EO	[235]	2021
Group teaching optimization algorithm (GTA)	GTA-AO	[235]	2021
Golden ratio optimization (GRO)	GREO	[236]	2020
Simulated annealing (SA)	BEOSA	[237]	2020

Table 6 Summary of the different research work carried out using Hybridized variants of EO algorithm

	Proposed Method	Year	Meta-Heuristic algorithm	Problems	Citation	Reference	Publisher
1	Self-adaptive quantum equilibrium optimizer with artificial bee colony (SQEOABC)	2023	Artificial bee colony (ABC)	Feature selection (COVID-19)	0	[135]	Elsevier
2	Hybrid teaching learning based optimization-equilibrium optimization (TLBO-EO)	2023	Teaching learning based optimization (TLBO)	Photo voltaic performance enhancement	0	[219]	Elsevier
3	Levy whale optimization mutation equilibrium optimizer (LWMEO)	2022	Whale optimization algorithm (WOA)	Engineering problems	5	[170]	Elsevier
4	Hybrid equilibrium optimizer with capsule auto encoder (HEOCAE)	2022	Adaptive fuzzy based atom search optimizer (AFASO) and adaptive rain optimization (ARO)	Multi class Alzheimer detection	3	[138]	Springer
5	Clustering and routing in WSN using genetic algorithm and equilibrium optimizer (GA-EO)	2022	Genetic algorithm (GA)	Clustering and routing in Wireless Sensor Networks (WSNs)	7	[223]	Wiley
6	equilibrium optimizer slime mould algorithm (EOSMA)	2022	Slime mould algorithm (SMA)	Engineering designs	7	[226]	Springer
7	Equilibrium-cuckoo search optimizer (ECSO)	2022	Cuckoo search optimizer (CS)	Multilevel threshold selection for colour satellite images	6	[229]	Elsevier
8	Clustering-based equilibrium optimizer and atom search optimization algorithm (CEOAS)	2022	Atom search optimization (ASO)	Speech emotion recognition	4	[230]	Springer
9	Hybrid multi-objective equilibrium optimizer and whale optimization algorithm (R2-HMEWO)	2022	Whale optimization algorithm (WOA)	Benchmark test problems	0	[221]	IEEE
10	Equilibrium optimizer slime mould algorithm (EOSMA) and a multi-objective EOSMA (MOEOSMA)	2022	Slime mould algorithm (SMA)	Kinematics (Robotic manipulator)	2	[227]	Nature
11	White Shark equilibrium optimizer (WSEO)	2022	White shark optimizer (WSO)	Power schedule problem- based internet of things (IoT)	0	[231]	IEEE
12	Modified equilibrium optimizer using teaching–learning-based optimization and opposition-based learning (OTLEO)	2022	Teaching learning-based optimization (TLBO)	Classical benchmark functions	0	[220]	IEEE
13	Equilibrium optimizer into slime mould algorithm (EOSMA)	2022	Slime mould algorithm (SMA)	Job shop scheduling problem	1	[228]	MDPI
14	Hybrid genetic algorithm- equilibrium Optimizer (GAEO)	2022	Genetic algorithm (GA)	Reactive power management	1	[224]	MDPI
15	Equilibrium whale optimization algorithm (EWOA)	2022	Whale optimization algorithm (WOA)	Benchmark test problems	0	[222]	Elsevier
16	Hybrid Genetic Algorithm Equilibrium optimizer (GAEO)	2022	Genetic algorithm (GA)	Distribution networks	1	[225]	Elsevier
17	Equilibrium optimizer- evaporation rate water cycle algorithm (EO–ERWCA)	2021	Evaporation rate water cycle algorithm (ERWCA)	Automatic voltage regulator (AVR) systems	6	[232]	MDPI
18	High balanced equilibrium optimizer (HEO)	2021	Thermal exchange optimization (TEO)	Engineering designs	6	[233]	Ios Press
19	Hybrid equilibrium optimizer (HEO)	2021	Grasshopper optimization algorithm (GOA)	Multi-level image segmentation	4	[234]	AIMS

Table 6 (continued)

	Proposed Method	Year	Meta-Heuristic algorithm	Problems	Citation	Reference	Publisher
20	Modified particle swarm optimization with equilibrium optimizer (MPSO-EO)	2021	Modified particle swarm optimization (MPSO)	Unit commitment problem (UCP)	7	[235]	MDPI
21	Group teaching optimization algorithm- Adaptive equilibrium optimizer (GTA-AO)	2021	Group teaching optimization algorithm (GTA)	MANET	0	[236]	Pre-Prints
22	Golden ratio based equilibrium optimization algorithm (GREO)	2020	Golden ratio optimization (GRO)	Feature selection for speech emotion recognition	27	[237]	IEEE
23	Binary equilibrium optimizer with simulated annealing (BEOSA)	2020	Simulated annealing (SA)	Feature selection	9	[238]	pre-prints

4.2.13 Hybridization with Modified Particle Swarm Optimization (MPSO)

Modified Particle Swarm Optimization with Equilibrium Optimization (MPSO-EO), which combines MPSO with EO to boost the population variety of EO and improve PSO's capacity to escape local minima, was proposed by Sayed et al. in the year 2021 [235]. Additionally, the experimental results clearly show that for the Unit Commitment Problem, the proposed MPSO-EO beats existing metaheuristics including EO, PSO, GWO, and SCA.

4.2.14 Hybridization with Group Teaching Optimization Algorithm (GTA)

In 2021, Hemalatha et al. [236] introduced a novel hybridized EO known as the Group Teaching Optimization Algorithm- Adaptive Equilibrium Optimizer (GTA-AO), which uses the GTA for route discovery and the AO for effective packet transmission. Furthermore, the experimental results clearly show that the suggested GTA-AO performs better than other approaches like B-iHTRP, HyphaNet, QNewBee, and Crowwhale-ETR in MANET.

4.2.15 Hybridization with Golden Ratio Optimization (GRO)

In 2021, Dey et al. [237] proposed a new hybridized EO variant known as the Golden Ratio based Equilibrium Optimization algorithm (GREO), which uses the Sequential One Point Flipping (SOPF) technique to find the closest neighbour of the final candidate solution vector and the Average Weighted Combination Mean (AWCM) to combine EO with GRO. Also, the experimental data clearly shows that the suggested GREO outperforms competing approaches for performing feature selection for speech emotion recognition, including SOLO-EO, SOLO-GRBA, PSO, ASO, SFO, GBO, GA, GWO, and HSO.

4.2.16 Hybridization with Simulated Annealing (SA)

Binary Equilibrium Optimizer with Simulated Annealing (BEOSA), a novel hybridized EO variant developed by Ghosh et al. in 2020 [238], uses SA to change the exploitative properties of EO. Also, the experimental results clearly show that the proposed BEOSA outperforms existing feature selection approaches, including BEO, GSA based, ALO based, GWO, and WOA.

Details of various metaheuristic algorithms hybridized with EO are shown in Table 5 below and the summary of the various research articles related to hybridized variants of EO proposed by various researchers that have been surveyed is tabulated in Table 6. Also, the full form of each acronym used in Table 6 is tabulated in Table 7.

3.

5 Applications Tackled by EO and Its Variants

EO and its variants have been employed to unravel assorted problems that belong to different application areas. The application areas and other related details are presented in Table 8.

6 Conclusion and Future research Directions

The goal of this study is to describe, discuss, and evaluate the most recent EO algorithms and their variations. From the study, it is evident that EO chooses a novel principle to handle optimization problems and has competitive advantages over other intelligent optimization algorithms, including ease of implementation, strong adaptability, fewer parameters, and the capacity to easily hybridize with other algorithms. Finding an optimal or nearly optimal solution is nevertheless difficult in some circumstances,

Table 7 The full form of each acronym used in Tables 2, 4 and 6

Full form of different algorithms/terminologies	Abbreviations
Equilibrium optimizer	EO
Photo voltaic	PV
Optimal power flow	OPF
Proportional derivative	PD
Unmanned ground vehicle	UGV
Distribution system	DS
Non-proliferative diabetic retinopathy	NPDR
Ventilation and air-conditioning	VAC
Tilt-integral-derivative with a fractional filter	TIDFF
Disturbance inspired equilibrium optimizer	DIEO
PV and battery energy storage	PES
Improved grey wolf optimizer	IGWO
Hunger game search	HGS
Atom search optimization	ASO
Hybrid firefly and particle swarm optimization	HFPSO
Laplacian Harris Hawk optimization	LHHO
Self-adaptive quantum equilibrium optimizer with artificial Bee colony	SQEOABC
Particle swarm optimization	PSO
Evolution strategy with covariance matrix adaptation	CMAES
Grey wolf optimizer	GWO
Salp swarm algorithm	SSA
Harris Hawks optimization	HHO
Slime mold algorithm	SMA
White Shark optimizer	WSO
Teaching–learning-slime mold algorithm	TLSMA
Directionally driven self-regulating particle swarm optimization	DDSRPSO
Elite evolutionary strategy- Harris Hawks optimization	EESHHO
Ameliorated equilibrium optimizer	AEO
Opposition-based learning	OBL
Centroid opposition-based learning	COBL
Unmanned ground vehicle	UGV
Self-adaptive equilibrium optimizer	self-EO
Teaching–learning-based optimization	TLBO
Sine cosine algorithm	SCA
Gravitational search algorithm	GSA
Adaptive gaining sharing knowledge	AGSK
Improved multi-operator differential evolution algorithm	IMODE
Minkowski-based equilibrium optimizer	MEO
Enhanced equilibrium optimizer	EEO
Multi-verse optimizer	MVO
Whale optimization algorithm	WOA
Binary particle swarm optimization with S-shape	BPOS/S
Binary particle swarm optimization with V-shape	BPSO/V
Binary dragonfly algorithm	BDA
Genetic algorithm	GA
ReliefF binary equilibrium optimizer with local search	RBEO-LS
Binary particle swarm optimization	BPSO
Henry gas solubility optimization	HGSO
Bat algorithm	BA
Normalized mutual information-based equilibrium optimizer	NMIEO
Extreme learning machine modified equilibrium optimizer	**ELM-MEO**

Table 7 (continued)

Full form of different algorithms/terminologies	Abbreviations
Levy whale optimization mutation equilibrium optimizer	LWMEO
Adaptive equilibrium optimizer	AEO
Improved equilibrium optimizer	IEO
Modified salp swarm algorithm	MSSA
Adaptive differential evolution	JADE
Equilibrium optimizer with divided population	DEO
Improved multi-objective equilibrium optimizer	IMOEO
Technique for order preference by similarity to ideal solution	TOPSIS
Binary improved equilibrium optimizer	BIMEO
Information-utilization strengthened equilibrium optimizer	IS-EO
Enhanced equilibrium optimizer	EEO
Photovoltaic modules and battery energy system combination	PV-BES
AV- binary modified equilibrium optimizer	AV-BMEO
Modified equilibrium optimizer	MEO
Iterative cosine operator	ICO
Residual moment-based joint damage index with equilibrium optimizer	RMBJDI-EO
Equilibrium optimizer -pattern search	EO-PS
Hybrid equilibrium optimizer with capsule auto encoder	HEOCAE
Adaptive fuzzy based atom search optimizer	AFASO
Adaptive rain optimization	ARO
Multi-objective equilibrium optimization technique	MOEOT
Hybrid equilibrium optimizer based on the crisscross strategy	HEOC
Affinity propagation based on optimization of preference	APBOP
Automatic niching differential evolution	ANDE
Automatic clustering based on dynamic parameters harmony search optimization algorithm	AC-DPHS
Automatic clustering based on mean artificial bee colony	AC-MeanABC
Relieff-guided novel binary equilibrium optimizer	RG-NBEO
Improved equilibrium optimizer based on levy flight	IEOLV
Multi-objective equilibrium optimizer algorithm integrated competition mechanism	CMOEO
Opposition-based learning	OBL
Multi-objective equilibrium optimizer algorithm integrated competition mechanism	CMOEO
Binary modified equilibrium optimizer	BMEO
Novel discrete equilibrium optimizer algorithm	NDEOA
Improved equilibrium optimizer regularized random vector functional link	IEO-RRVFL
Opposition equilibrium optimizer	OEO
Segmentation score	SS
Segmentation error minimization	SEM
Opposition equilibrium optimizer	OEO
Improved equilibrium optimizer	IEO
Opposition-based laplacian equilibrium optimizer algorithm	O-LEO
Binary version of the equilibrium optimization algorithm	BEOA
Binary grey wolf optimizer	BGWO
Binary particle swarm optimizer	BPSO
Binary whale optimizer	BWO
Binary slime mould optimizer	BSMO
Binary grasshopper optimizer	BGO
Binary artificial ecosystem optimizer	BAEO
Binary elephant herding optimizer	BEHO
Simulated annealing	SA
Harmony search algorithm	HSA

Table 7 (continued)

Full form of different algorithms/terminologies	Abbreviations
Bacterial foraging optimization algorithm	BFOA
Backtracking search optimization algorithm	BSOA
Binary version of the equilibrium optimizer	BEO
Binary bat algorithm	BBA
Binary differential evolution	BDA
Binary hybrid particle swarm optimization and gravitational search algorithm	BHPSOGSA
Hybrid fuzzy equilibrium optimizer	HFEO
Moth-flame optimization algorithm	MFO
Grasshopper optimization algorithm	GOA
Flower pollination algorithm	FPA
R_2 index hybrid multi-objective equilibrium optimization algorithm	R_2HMEOA
Non-dominated sorting genetic algorithm III	NSGA-II
Non-dominated sorting genetic algorithm III	NSGA-III
Multi-objective spotted hyena optimizer	MOSHO
Multi-objective evolutionary algorithm	MOEA
Improved version of equilibrium optimizer	I-EO
Dimension learning hunting	DLH
Improved version of equilibrium optimizer	I-EO
Adaptive guided differential evolution	AGDA
Tunicate swarm algorithm	TSA
Classification rule mining using a discrete equilibrium optimization algorithm	DEOA-CRM
Ant colony classification mining algorithm based on pheromone attraction and exclusion	AntMiner-PAE
Hybrid ant colony optimization and iterated local search for rule-based classification	ILS-AntMiner
Discrete equilibrium optimizer simulated annealing	DEOSA
Discrete equilibrium optimizer	DEO
Gravitational search algorithm	GSA
Binary variant of ant lion optimizer	BALO
Hybrid genetic simulated annealing	HGSA
Deluge based genetic algorithm	DGA
Clustering population based binary gravitational search algorithm	CPBGSA
Multi-strategy improved equilibrium optimizer	**IEO**
Lens opposition-based learning	**LOBL**
Grouping gravitational search algorithm	GGSA
Hierarchical gravitational search algorithm	HGSA
Random grouping brain storm optimization	RGBSO
Modified equilibrium optimizer	MEO
Adaptive equilibrium optimizer	AEO
Opposition-based laplacian equilibrium optimizer	OB-L-EO
High equilibrium optimizer	HEO
Disturbance-inspired equilibrium optimizer	DIEO
Hunger game search	HGS
Autonomous group's particle swarm optimization	AGPSO
Binary equilibrium optimization algorithm	BEOA
Support vector machine	SVM
K nearest neighbor	K-NN
Naïve bayes	NB
Chaotic equilibrium optimizer algorithm	CEO
Quantum artificial bee colony	QABC
Chicken swarm optimization	CSO
Multi-objective equilibrium optimization	MOEO

Table 7 (continued)

Full form of different algorithms/terminologies	Abbreviations
Multi-objective particle swarm optimization	MOPSO
Artificial ecosystem optimization	AEO
Cuckoo search algorithm	CSA
Teaching–learning-based optimization	TLBO
United equilibrium optimizer	UEO
Evolution strategy with covariance matrix adaptation (CMA-ES)	CMA-ES
Parallel equilibrium optimizer	UEO
Parallel particle swarm optimization	PPSO
Capacitated vehicle routing problem (CVRP)	CVPR
Enhanced equilibrium optimizer	E2O
Stochastic multi parameter optimization	SMPO
Discreet stochastic optimization	DSO
Enhanced equilibrium optimizer	EEO
Automata-based improved equilibrium optimizer with U-shaped transfer function	AIEOU
Social ski driver algorithm with late acceptance hill climbing	SSDs + LAHC
Ring theory-based harmony search	RTHS
Adaptive β binary sailfish optimizer	AβBSF
Hybrid serial gray-whale optimizer	HSGW
Random switching serial gray-whale optimizer	RSGW
Adaptive switching gray-whale optimizer	ASGW
Binary genetic algorithm	BGA
Advanced equilibrium optimizer	AEO
Compact equilibrium optimizer	cEO
Multi-objective dynamic random neighborhood particle swarm optimization	DRN-PSO
Non-dominated sorting genetic algorithm	NSGA
Niched pareto genetic algorithm	NPGA
Fuzzy clustering based particle swarm optimization	FCPSO
Modified shuffled frog leaping algorithm	MSFLA
Real coded genetic algorithm	RCGA
Strength pareto evolutionary algorithm	SPEA
Constrained multiobjective equilibrium optimizer algorithm	CMEO
Combined economic emission dispatch problem	CEEDP
Interswarm interactive learning strategy equilibrium optimizer	IILEO
Improved salp swarm algorithm	ISSA
Improved equilibrium optimization algorithm (IEOA)	IEOA
Elite opposition-based learning	EOBL
General learning equilibrium optimization	GLEO
Relieff algorithm	FR
Binary version of the equilibrium optimization	BEO
Greedy search algorithm	GSA
Branch and bound algorithm	BB
Modified equilibrium optimizer	m-EO
Orikaeshi Tanren SA	OTSA
Opposition based SCA	OBSCA
Selective opposition-based GWO	SOGWO
Harmony search	HS
Social spider optimization	SSO
Firefly algorithm	FA
Firefly algorithm social spider optimization	FASSO
Multi-objective equilibrium optimizer	MOEO
Multi-objective equilibrium optimizer improved using sine function	MOEOS

Table 7 (continued)

Full form of different algorithms/terminologies	Abbreviations
Multi-objective equilibrium optimizer with exploration–exploitation dominance strategy	MOEO-EED
Multi-objective equilibrium optimizer with exploration–exploitation dominance strategy- Gaussian-based mutation (G) strategy	MOEO-EED-G
Opposition-based multi-objective equilibrium optimizer with exploration–exploitation dominance strategy-gaussian-based mutation (G) strategy	OMOEO-EED-G
Multi-objective equilibrium optimizer improved using the linear function	MOEOL
Multi-objective equilibrium optimizer improved using the cosine function	MOEOC
Multi-objective equilibrium optimizer improved using the tan function	MOEOT
Multi-objective equilibrium optimizer improved using the exponential function	MOEOT
Multi-objective equilibrium optimizer improved using the log function	MOEOLog
Non-dominated sorting genetic algorithm II	NSGA II
Speed-constrained multi-objective particle swarm optimization	SMPSO
Parallel evolutionary algorithms	PAE
Hypervolume metric selection evolutionary multiobjective optimization algorithm	SMSEMOA
Improvement-based reference points method	IBRPM
Decision variable clustering-based evolutionary algorithm for large-scale many-objective optimization	LMEA
Efficient large-scale multi-objective optimization based on a competitive swarm optimizer	LMOCSO
An indicator-based multi-objective evolutionary algorithm with reference point adaptation	ARMOEA
An adaptive evolutionary algorithm based on non-euclidean geometry for many-objective optimization	AGEMOEA
Clustering-based adaptive evolutionary algorithm for multiobjective optimization with irregular pareto fronts	CAMOEA
Two-archive evolutionary algorithm for constrained multi-objective optimization	CTAEA
A competitive mechanism based multi-objective particle swarm optimizer with fast convergence	CMOPSO
Constrained decomposition with grids	CDG
High equilibrium optimizer	HEO
Thermal exchange optimization	TEO
Hybrid equilibrium optimizer	HEO
Kill herd algorithm	KHA
Stud kill herd algorithm	SKHA
Adaptive real coded biogeography-based optimization	ARCBBO
Levy spiral flight equilibrium optimizer	LSFEO
Chaotic search based constrained equilibrium optimizer algorithm	CS-CEOA
Modified equilibrium optimization algorithm-based interval type-2 fuzzy proportional integral derivative controller	MEO-IT2FPID
Optimal power flow	OPF
Opposition-based equilibrium optimization	OBEO
Particle swarm optimization grey wolf optimization	PSOGWO
Grey wolf optimization and cuckoo search	GWOCS
Seagull optimization algorithm	SOA
Coyote optimization algorithm	COA
Carnivorous plant algorithm	CPA
Transient search algorithm	TSA
Long short-term memory	LSTM
Multiple population hybrid equilibrium optimizer	MHEO
Unmanned aerial vehicle	UAV
Hybrid firefly and particle swarm optimization	HFPSO
Grey wolf optimizer using gaussian estimation of distribution	GEDGWO

Table 7 (continued)

Full form of different algorithms/terminologies	Abbreviations
Virus colony search	VCS
Disruption-based multi-objective equilibrium optimization algorithm	DMOEAO
Layered disruption method	LDM
Multi-objective particle swarm optimization	MOPSO
Multi-objective ant lion optimizer	MOALO
Multi-objective whale optimization algorithm	MOWOA
Multi-objective grey wolf optimizer	MOGWO
Binary equilibrium optimizer algorithm based on S transfer function	BEO-S
Binary equilibrium optimizer algorithm based on v transfer function	BEO-V
Binary equilibrium optimizer algorithm based on target	BEO-T
Random walk equilibrium optimizer algorithm	RW-EOA
Modified equilibrium optimizer	m-EO
Adaptive equilibrium optimizer	AEO
Squirrel search algorithm	SSA
Wind driven optimization	WDO
Linear reduction diversity	LRD
Minima elimination method	MEM
Classified perturbation mutation based particle swarm optimization	CPMPSO
Memetic adaptive differential evolution	MADE
Improved teaching learning-based optimization	ITLBO
Multiple learning backtracking search algorithm	MLBSA
Multi-trial vector-based differential evolution	MTDE
Equilibrium optimizer slime mould algorithm	EOSMA
Equilibrium-cuckoo search optimizer	ECSO
Cuckoo search algorithm	CSA
Differential exponential entropy	DEE
Clustering-based equilibrium optimizer and atom search optimization algorithm	CEOAS
Multi-objective evolutionary algorithm based on decomposition	MOEA/D
Multi-objective evolutionary algorithm based inverted generational distance metric-noncontributing solutions	MOEA/IGD-NS
Many-objective metaheuristic based on the R2 indicator	MOMBI-II
Dynamic multi-objective particle swarm optimization	dMOPSO
Equilibrium optimizer slime mould algorithm	EOSMA
Multi-objective equilibrium optimizer slime mould algorithm	MOEOSMA
Hybrid grey wolf—equilibrium optimizer	HGW-EO
White shark equilibrium optimizer	WSEO
Dwarf mongoose optimization algorithm	DMOA
Modified equilibrium optimizer using teaching–learning-based optimization and opposition-based learning	OTLEO
Teaching learning-based optimization	TLBO
Equilibrium optimizer into slime mould algorithm	EOSMA
Centroid opposition-based computation	COBC
Bald eagle search	BES
Aquila optimizer	AO
Genetic algorithm-equilibrium optimization	GAEO
Chaotic bat algorithm	CBA
Improved salp swarm algorithm	ISSA
Equilibrium whale optimization algorithm	EWOA
Dwarf mongoose optimization algorithm	DMOA
Pelican optimization algorithm	POA
Dingoes optimization algorithm	DOA

Table 7 (continued)

Full form of different algorithms/terminologies	Abbreviations
Arithmetic optimization algorithm	AOA
Hybrid genetic algorithm equilibrium optimizer	GAEO
Genetic algorithms and satin bowerbird optimization	GASBO
Satin bowerbird optimization	SBO
Bacterial foraging optimization algorithm	BFOA
Simulated annealing	SA
Quasi-oppositional teaching–learning based optimization	QOTLBO
improved analytical method	IA
CuttleFish algorithm	CFA
Equilibrium optimizer- evaporation rate water cycle algorithm	EO-ERWCA
Yellow saddle goatfish algorithm	YSGA
Cuckoo search	CS
High equilibrium optimizer	HEO
Hybrid equilibrium Optimizer	HEO
Modified particle swarm optimization with equilibrium optimizer	MPSO-EO
Modified particle swarm optimization	MPSO
Unit commitment problem	UCP
Bio-inspired hybrid routing protocol	B-iHTRP
Golden ratio based equilibrium optimization algorithm	GREO
Average weighted combination mean	AWCM
Sequential one point flipping	SOPF
Binary equilibrium optimizer with simulated annealing	BEOSA
Bi-phase mutation based equilibrium optimizer	BMHEO
Bi-phase mutation	BM

especially when facing difficult multi-modal problems, for a variety of reasons:

1. The great propensity to become trapped in local optima (local optima stagnation).
2. Slow convergence speed and
3. The discrepancy points to an immature equilibrium between extraction and exploration.

Major reasons for the above-mentioned issues with EO are:

1. Low quality initial population particles are generated randomly.
2. An uneven exploration and exploitation process during iterative phase and
3. Most significantly, population diversity is reduced as a result of particle aggregation in the latter iteration phase.

This prompted the development and launch of various EO variations to address the shortcomings and problems with the original algorithm and make it into a more powerful, reliable, and efficient algorithm that could handle a variety of search areas. Therefore, the study represents an up-to-date survey on EO and its different variants, along with their applications in different optimization fields. This review paper includes 175 research articles related to the EO algorithm published in numerous reputed journals and conferences since its inception in the year 2020 until January 2023. According to the research so far, it is evident that the EO algorithm has become quite well-known and important, which has led to introduction of 87 different methods as the revised variants of EO since 2020 to resolve problems in various application areas. Above all, the basic and revised EO have been integrated with the existing metaheuristic algorithms, resulting in the development of 23 new hybrid algorithms to address a wide variety of issues from numerous research disciplines.

Additionally, the following limitations are based on the articles surveyed:

1. PF problems, PV systems, distribution system networks, feature selection, and engineering design problems have all seen extensive use of EO.
2. Levy flight and Opposition-based Learning are most frequently utilized strategies to boost the performance of EO.
3. Although chaotic sequence, fuzzy, and quantum mechanisms have been used, they have not been thoroughly investigated.

Table 8 Application areas covered by EO and its variants

Problems/Application areas	Year	References	Variants of EO
Wind Power speed assessment	2023	[64]	Basic EO
NPDR classification	2022	[65]	Basic EO
Power system networks	2022	[66]	Basic EO
OPF problem	2022	[67]	Basic EO
	2020	[126]	Basic EO
	2022	[133, 212]	Revised EO
	2021	[174]	Revised EO
TIDFF controllers	2022	[68]	Basic EO
PV systems	2022	[69, 73, 74, 80]	Basic EO
	2021	[87, 96, 106, 107, 109, 112, 115]	Basic EO
	2021	[196, 216]	Revised EO
	2020	[218]	Revised EO
	2022	[177, 178, 203]	Revised EO
	2023	[219]	Hybridized EO
Power system problems	2022	[70]	Basic EO
Fault pole identification	2022	[71]	Basic EO
Reconfiguration of distribution system network	2022	[72, 75, 76, 83]	Basic EO
	2021	[94, 99]	Basic EO
	2022	[208]	Revised EO
	2022	[225]	Hybridized EO
Power flow calculations of power systems	2022	[77]	Basic EO
End-milling process	2022	[78]	Basic EO
PD controller	2022	[79]	Basic EO
Stock market prediction	2022	[81]	Basic EO
Damage detection	2022	[84]	Basic EO
Mechanical design problems	2021	[85]	Basic EO
Medical image fusion	2021	[86]	Basic EO
Real-world classification problems	2021	[88]	Basic EO
Local trajectory planning of UGV	2021	[89]	Basic EO
Optimal allocation in distributed systems	2021	[90]	Basic EO
Parameter estimation of Solar Cells	2021	[91]	Basic EO
PEM fuel cell system	2021	[92]	Basic EO
Thermoelectric power generation systems	2021	[93]	Basic EO
Medical image fusion	2021	[95]	Basic EO
Fuel cell dynamic model	2021	[97]	Basic EO
Data mining	2021	[98]	Basic EO
Automatic voltage regulator system controller	2021	[100]	Basic EO
Medical image fusion	2021	[101]	Basic EO
Network reconfiguration and distributed generation allocation in power systems	2021	[102]	Basic EO
Magnetic levitation system	2021	[103]	Basic EO
Renewable energy system	2021	[104]	Basic EO
Micro-grid power systems	2021	[105]	Basic EO
	2020	[125]	Basic EO
Linear and circular antenna arrays	2021	[108]	Basic EO
Brushless direct current wheel motor design problem	2021	[111]	Basic EO
Wind turbine	2021	[113]	Basic EO
Traveling Salesman problem	2021	[114]	Basic EO
Wind generation units	2021	[115]	Basic EO
VAC system	2021	[116]	Basic EO

Table 8 (continued)

Problems/Application areas	Year	References	Variants of EO
Wind energy control system	2021	[117]	Basic EO
Rainfall-runoff modelling	2021	[118]	Basic EO
Forecasting and eliminating tremors in teleoperation	2021	[119]	Basic EO
Renewable micro-grids	2021	[120]	Basic EO
Solar dish collector	2021	[121]	Basic EO
Economic dispatch problem	2020	[122]	Basic EO
Schottky diode parameter estimation	2020	[123]	Basic EO
Hybrid AC/DC grids	2020	[124]	Basic EO
Interconnected power systems	2020	[127, 131]	Basic EO
	2022	[132, 207]	Revised EO
Traffic transportation prediction	2020	[128]	Basic EO
MANET	2020	[129]	Basic EO
	2021	[236]	Hybridized EO
Prediction of laser cutting parameters	2020	[130]	Basic EO
COVID-19 feature selection/diagnosis/segmentation	2023	[135, 200]	Revised EO
	2022	[209]	Revised EO
Path planning of the unmanned ground vehicle (UGV)	2023	[186]	Revised EO
Medical dataset classification	2023	[201]	Revised EO
Global, combinatorial, engineering and multi-objective problems	2022	[136]	Revised EO
Job Shop scheduling problem	2022	[202]	Revised EO
	2022	[228]	Hybridized EO
Optimal control problems (Building and construction industry)	2022	[155]	Revised EO
Feature selection	2022	[82]	Basic EO
	2021	[110]	Basic EO
	2022	[137, 144, 146, 156–159, 163, 165, 173]	Revised EO
	2021	[140, 167, 192]	Revised EO
	2020	[169]	Revised EO
	2021	[238]	Hybridized EO
	2020	[237]	Hybridized EO
Soil compression index prediction (roadways, railways and airport runways)	2022	[151]	Revised EO
Engineering design problems	2023	[184]	Revised EO
	2022	[170, 187, 191]	Revised EO
	2021	[148, 193]	Revised EO
	2022	[226]	Hybridized EO
	2021	[233]	Hybridized EO
Optimal scheduling of residential houses	2022	[176]	Revised EO
Joint damage identification	2022	[204]	Revised EO
DNA storage	2022	[172]	Revised EO
Engineering optimization problems	2022	[171]	Revised EO
Wind farm layout optimization Problems	2022	[206]	Revised EO
Global optimization problem	2022	[146]	Revised EO
Multi-objective optimization problem	2022	[180]	Revised EO
	2021	[152, 182]	Revised EO
Multi class alzheimer detection	2022	[138]	Revised EO
Hyperspectral image classification	2022	[160]	Revised EO
Classification rule generation	2022	[161, 164]	Revised EO
Color constancy	2022	[188]	Revised EO
Cloud-based healthcare services paradigm (HCS)	2022	[190]	Revised EO

Table 8 (continued)

Problems/Application areas	Year	References	Variants of EO
Domination metric dimension problem	2022	[162]	Revised EO
Estimation of size and location of Distributed Generators	2022	[142]	Revised EO
Mine ventilation system	2022	[179]	Revised EO
Hydrogeological parameters identification Problems	2022	[145]	Revised EO
Optimal reactive power Dispatch (ORPD) problem	2022	[211]	Revised EO
Sentiment analysis	2022	[166]	Revised EO
Multi-modal image registration	2021	[134]	Revised EO
Capacitated vehicle routing problem (cvrp)	2021	[197]	Revised EO
Hover flight system	2021	[213]	Revised EO
Optimal control designs	2021	[214]	Revised EO
Electric vehicle routing problem with time windows (EVRPTW)	2021	[199]	Revised EO
Power system network	2021	[198]	Revised EO
Combined economic emission dispatch problem (CEEDP)	2021	[181]	Revised EO
UAV path planning problem	2021	[153, 185]	Revised EO
Biological data classification	2021	[215]	Revised EO
0–1 Knapsack problem	2021	[168]	Revised EO
Image segmentation	2021	[194]	Revised EO
	2022	[189]	Revised EO
	2021	[234]	Hybridized EO
Multilevel thresholding	2022	[139]	Revised EO
	2021	[195]	Revised EO
	2020	[141]	Revised EO
	2023	[229]	Hybridized EO
Frequency control of an AC microgrid	2021	[143]	Revised EO
Non-linear programming and petrochemical application	2021	[147]	Revised EO
Neural network	2022	[210]	Revised EO
	2021	[149]	Revised EO
Structural optimization	2020	[183]	Revised EO
Numerical optimization	2020	[154]	Revised EO
Clustering and routing in wireless sensor networks	2022	[223]	Hybridized EO
Speech emotion recognition	2022	[230]	Hybridized EO
Benchmark functions	2020	[150, 175, 217]	Revised EO
	2022	[220–222]	Hybridized EO
Kinematics (Robotic manipulator)	2022	[227]	Hybridized EO
Power schedule problem- based internet of things (IoT)	2022	[231]	Hybridized EO
Reactive power management	2022	[224]	Hybridized EO
Automatic voltage regulator (AVR) systems	2021	[232]	Hybridized EO
Unit commitment problem (UCP)	2021	[235]	Hybridized EO

Without a doubt, EO and its variations have demonstrably proven to be successful methods for resolving ambiguous optimization challenges in the real world, but more research is still needed. Some of the potential research routes have been anticipated here, and maybe they will prove useful for the researcher as they dig up and uncover EO in other research fields.

1. To concentrate on the development of revised variants of EO capable of not only improving exploration and exploitation ability and avoiding local stagnation issues, but also focusing on diversity of solutions, expansion of algorithm's search range, and so on, by introducing a *multi-strategy optimization mechanism* incorporating strategies that shall evenly distribute the particles in the search space rather than random initialization; one or more dynamic control parameter strategies to create

exploration and exploitation stability; to include strategies in late iteration phases to avoid the algorithm from entering into local optima and particle aggregation.

2. EO has so far been created in a variety of forms (Table 4), and all of the variations have shown to produce the finest outcomes across many research fields; yet *Mixed-integer* EO (MEO), *Parameter-less* EO (PEO), *Quantum-inspired* EO(QEO), *Fuzzy-controlled* EO (FEO), etc., could be worthwhile to investigate this further in the future.
3. As listed in Table 6 of Sect. 4.2, many swarm-based [239] and human-based meta-heuristic algorithms [240] have been combined with EO for different types of optimization problems. Further applications or integrations of other NIOA algorithm [241] types are possible, such as Plant-based, Maths-based or even Physics-Chemistry-based meta-heuristic algorithms [242, 243], to determine the EO's potential, improve computational performance, and produce good solutions.
4. Table 8 of Sect. 5 brings to light the usage of EO in countless application areas; however, very little work has been proposed using EO for path forecasting and map reading. However, more rigorous versions of EO might be developed, such as Itinerant EO, which should be able to handle and control dynamic routes, barriers, goals, etc. This would undoubtedly be an excellent topic to work in the future.
5. In a similar line, EO technology could be additionally stretched to work on diverse optimization problems namely, Energy storage devices, Smart grids, Knowledge discovery systems, Fog systems, Abrupt motion tracking, DNA fragment assembly problems, Electric Car component design, Production planning, Rule mining, Image encryption and decryption, Vehicle routing problems, Shrimp freshness detection, Signal denoising, Pathology Image Clustering [244, 245], Work scheduling, Multi-objective feature selection, Smart home applications etc.
6. Also, the application of EO to resolving discrete problems could be a new area to ponder.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors declare that they have no conflict of interest.

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

References

1. Fausto F, Reyna-Orta A, Cuevas E, Andrade ÁG, Perez-Cisneros M (2020) From ants to whales: metaheuristics for all tastes. Artif Intell Rev 53(1):753–810
2. Dorigo M Di Caro G (1999) Ant colony optimization: a new meta-heuristic. In: Proceedings of the 1999 congress on evolutionary computation-CEC99 (Cat. No. 99TH8406). IEEE vol 2 pp 1470–1477
3. Yang XS, Deb S (2010) Engineering optimisation by cuckoo search. arXiv preprint arXiv:1005.2908
4. Karaboga D (2010) Artificial bee colony algorithm. Scholarpedia 5(3):6915
5. Kennedy J, Eberhart R (1995, November) Particle swarm optimization. In Proceedings of ICNN'95-international conference on neural networks. IEEE. (Vol. 4, pp. 1942–1948)
6. Yang XS, He X (2013) Firefly algorithm: recent advances and applications. arXiv preprint arXiv:1308.3898
7. Wang GG, Guo L, Gandomi AH, Hao GS, Wang H (2014) Chaotic krill herd algorithm. Inform Sci 274:17–34
8. Yang XS, Gandomi AH (2012) Bat algorithm: a novel approach for global engineering optimization. Eng Comput. https://doi.org/10.1108/02644401211235834
9. Zhao W, Zhang Z, Wang L (2020) Manta ray foraging optimization: an effective bio-inspired optimizer for engineering applications. Eng Appl Artif Intell 87:103300
10. Mirjalili S (2015) Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm. Knowl-Based Syst 89:228–249
11. Mirjalili S (2016) Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems. Neural Comput Appl 27(4):1053–1073
12. Faramarzi A, Heidarinejad M, Mirjalili S, Gandomi AH (2020) Marine predators algorithm: a nature-inspired metaheuristic. Expert Syst Appl 152:113377
13. Emary E, Zawbaa HM, Grosan C, Hassenian AE (2015). Feature subset selection approach by gray-wolf optimization. In Afro-European conference for industrial advancement. Springer, Cham. (pp. 1–13)
14. Mirjalili S, Lewis A (2016) The whale optimization algorithm. Adv Eng Softw 95:51–67
15. Lam A, Li VO (2012) Chemical reaction optimization: a tutorial. Memetic Computing 4(1):3–17
16. Hashim FA, Houssein EH, Mabrouk MS, Al-Atabany W, Mirjalili S (2019) Henry gas solubility optimization: A novel physics-based algorithm. Futur Gener Comput Syst 101:646–667
17. Alatas B (2011) ACROA: artificial chemical reaction optimization algorithm for global optimization. Expert Syst Appl 38(10):13170–13180
18. Shi Y (2011, June). Brain storm optimization algorithm. In International conference in swarm intelligence. Springer, Berlin, Heidelberg. (pp. 303–309)
19. Rao RV, Savsani VJ, Vakharia DP (2011) Teaching–learning-based optimization: a novel method for constrained mechanical design optimization problems. Comput Aided Des 43(3):303–315
20. Das P, Das DK, Dey S (2018) A new class topper optimization algorithm with an application to data clustering. IEEE Trans Emerg Top Comput 8(4):948–959
21. Atashpaz-Gargari E, Lucas C (2007, September) Imperialist competitive algorithm: an algorithm for optimization inspired

by imperialistic competition. In 2007 IEEE congress on evolutionary computation. (pp. 4661–4667)
22. Mousavirad SJ, Ebrahimpour-Komleh H (2017) Human mental search: a new population-based metaheuristic optimization algorithm. Appl Intell 47(3):850–887
23. Shabani A, Asgarian B, Salido M, Gharebaghi SA (2020) Search and rescue optimization algorithm: A new optimization method for solving constrained engineering optimization problems. Expert Syst Appl 161:113698
24. Emami H, Derakhshan F (2015) Election algorithm: a new socio-politically inspired strategy. AI Commun 28(3):591–603
25. Mohamed AW, Hadi AA, Mohamed AK (2020) Gaining-sharing knowledge based algorithm for solving optimization problems: a novel nature-inspired algorithm. Int J Mach Learn Cybern 11(7):1501–1529
26. Shaheen AM, Ginidi AR, El-Sehiemy RA, Ghoneim SS (2020) A forensic-based investigation algorithm for parameter extraction of solar cell models. IEEE Access 9:1–20
27. Fadakar E, Ebrahimi M (2016, March) A new metaheuristic football game inspired algorithm. In 2016 1st conference on swarm intelligence and evolutionary computation (CSIEC). IEEE. (pp. 6–11)
28. Khatri A, Gaba A, Rana KPS, Kumar V (2020) A novel life choice-based optimizer. Soft Comput 24(12):9121–9141
29. Al-Betar MA, Alyasseri ZAA, Awadallah MA, Abu Doush I (2021) Coronavirus herd immunity optimizer (CHIO). Neural Comput Appl 33(10):5011–5042
30. Rahkar Farshi T (2021) Battle royale optimization algorithm. Neural Comput Appl 33(4):1139–1157
31. Cai W, Yang W, Chen X (2008, October) A global optimization algorithm based on plant growth theory: plant growth optimization. In 2008 International conference on intelligent computation technology and automation (ICICTA). IEEE. (Vol. 1, pp. 1194–1199)
32. Murase H (2000) Finite element inverse analysis using a photosynthetic algorithm. Comput Electron Agric 29(1–2):115–123
33. Salhi A, Fraga ES (2011) Nature-inspired optimisation approaches and the new plant propagation algorithm
34. Cui Z, Cai X (2013) Artificial plant optimization algorithm. In Swarm Intelligence and Bio-Inspired Computation. Elsevier. (pp. 351–365)
35. Kong X, Chen YL, Xie W, Wu X (2012, June) A novel paddy field algorithm based on pattern search method. In 2012 IEEE international conference on information and automation. IEEE. (pp. 686–690)
36. Akyol S, Alatas B (2017) Plant intelligence based metaheuristic optimization algorithms. Artif Intell Rev 47(4):417–462
37. Mohammadi M, Khodaygan S (2020) An algorithm for numerical nonlinear optimization: Fertile Field Algorithm (FFA). J Ambient Intell Humaniz Comput 11(2):865–878
38. Yang, X. S. (2012, September). Flower pollination algorithm for global optimization. In International conference on unconventional computing and natural computation. Springer, Berlin, Heidelberg. (pp. 240–249)
39. Zhou Y, Wang Y, Chen X, Zhang L, Wu K (2017) A novel path planning algorithm based on plant growth mechanism. Soft Comput 21(2):435–445
40. Karimkashi S, Kishk AA (2010) Invasive weed optimization and its features in electromagnetics. IEEE Trans Antennas Propag 58(4):1269–1278
41. Labbi Y, Attous DB, Gabbar HA, Mahdad B, Zidan A (2016) A new rooted tree optimization algorithm for economic dispatch with valve-point effect. Int J Electr Power Energy Syst 79:298–311
42. Karci A (2007, April) Theory of saplings growing up algorithm. In International Conference on Adaptive and Natural Computing Algorithms. Springer, Berlin, Heidelberg (pp. 450–460)
43. Zhang H, Zhu Y, Chen H (2014) Root growth model: a novel approach to numerical function optimization and simulation of plant root system. Soft Comput 18(3):521–537
44. Karami H, Sanjari MJ, Gharehpetian GB (2014) Hyper-Spherical Search (HSS) algorithm: a novel meta-heuristic algorithm to optimize nonlinear functions. Neural Comput Appl 25(6):1455–1465
45. Rahmani R, Yusof R (2014) A new simple, fast and efficient algorithm for global optimization over continuous search-space problems: radial movement optimization. Appl Math Comput 248:287–300
46. Salimi H (2015) Stochastic fractal search: a powerful metaheuristic algorithm. Knowl-Based Syst 75:1–18
47. Nematollahi AF, Rahiminejad A, Vahidi B (2020) A novel metaheuristic optimization method based on golden ratio in nature. Soft Comput 24(2):1117–1151
48. Mirjalili S (2016) SCA: a sine cosine algorithm for solving optimization problems. Knowl-Based Syst 96:120–133
49. Gabis AB, Meraihi Y, Mirjalili S, Ramdane-Cherif A (2021) A comprehensive survey of sine cosine algorithm: variants and applications. Artif Intell Rev 54(7):5469–5540
50. Abualigah L, Diabat A, Mirjalili S, Abd Elaziz M, Gandomi AH (2021) The arithmetic optimization algorithm. Comput Methods Appl Mech Eng 376:113609
51. Faramarzi A, Heidarinejad M, Stephens B, Mirjalili S (2020) Equilibrium optimizer: a novel optimization algorithm. Knowl-Based Syst 191:105190
52. Mirjalili S, Mirjalili SM, Hatamlou A (2016) Multi-verse optimizer: a nature-inspired algorithm for global optimization. Neural Comput Appl 27(2):495–513
53. Erol OK, Eksin I (2006) A new optimization method: big bang–big crunch. Adv Eng Softw 37(2):106–111
54. Zhao W, Wang L, Zhang Z (2019) Atom search optimization and its application to solve a hydrogeologic parameter estimation problem. Knowl-Based Syst 163:283–304
55. Formato RA (2007) Central force optimization. Prog Electromagn Res 77(1):425–491
56. Kaveh A, Dadras A (2017) A novel meta-heuristic optimization algorithm: thermal exchange optimization. Adv Eng Softw 110:69–84
57. Kaveh A, Khayatazad M (2012) A new meta-heuristic method: ray optimization. Comput Struct 112:283–294
58. Rashedi E, Nezamabadi-Pour H, Saryazdi S (2009) GSA: a gravitational search algorithm. Inf Sci 179(13):2232–2248
59. Xie L, Tan Y, Zeng J, Cui Z (2010) Artificial physics optimisation: a brief survey. Int J Bio-Inspired Comput 2(5):291–302
60. Kashan AH (2015) A new metaheuristic for optimization: optics inspired optimization (OIO). Comput Oper Res 55:99–125
61. Abedinpourshotorban H, Shamsuddin SM, Beheshti Z, Jawawi DN (2016) Electromagnetic field optimization: a physics-inspired metaheuristic optimization algorithm. Swarm Evol Comput 26:8–22
62. Rashedi E, Rashedi E, Nezamabadi-Pour H (2018) A comprehensive survey on gravitational search algorithm. Swarm Evol Comput 41:141–158
63. Birbil Şİ, Fang SC (2003) An electromagnetism-like mechanism for global optimization. J Global Optim 25(3):263–282
64. Alham MH, Gad MF, Ibrahim DK (2023) Potential of wind energy and economic assessment in Egypt considering optimal hub height by equilibrium optimizer. Ain Shams Eng J 14(1):101816
65. Amin J, Anjum MA, Malik M (2022) Fused information of DeepLabv3+ and transfer learning model for semantic segmentation

and rich features selection using equilibrium optimizer (EO) for classification of NPDR lesions. Knowl-Based Syst 249:108881
66. Gani SMA, Islam MR, Shafiullah M, Tayeb JH, Hossain MI, Ali A (2022, February) Equilibrium optimizer for LFO damping in multimachine power system networks. In 2022 International Conference on Advancement in Electrical and Electronic Engineering (ICAEEE). IEEE. (pp. 1–6)
67. Amroune M (2022) Wind integrated optimal power flow considering power losses, voltage deviation, and emission using equilibrium optimization algorithm. Energy Ecol Environ 7(4):369–392
68. Gulicer AK, Ayas MS (2022, June) Employing equilibrium optimizer in two-area load frequency control for a TIDFF controller design. In 2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA). IEEE. (pp. 1–5)
69. Zabia DE, Afghoul H, Kraa O (2022, October) A novel equilibrium optimizer for tracking the maximum power of a photovoltaic system under non-uniform conditions. In 2022 2nd International Conference on Advanced Electrical Engineering (ICAEE). IEEE. (pp. 1–6)
70. Prakasa MA, Robandi I (2022, July) Power system stabilizer tuning improvement for single-machine infinite bus using equilibrium optimizer algorithm. In 2022 International Seminar on Intelligent Technology and Its Applications (ISITIA). IEEE. (pp. 320–325)
71. Li Q, Tian S, Huang X, Deng J, Guo Z, Yang B (2022, July). Random forest-equilibrium optimizer based HVDC fault diagnosis with renewable energy integration. In 2022 4th International Conference on Power and Energy Technology (ICPET). IEEE. (pp. 451–455)
72. Hashem M, Abdel-Salam M, Nayel M, El-Mohandes MT (2022) A Bi-level optimizer for reliability and security assessment of a radial distribution system supported by wind turbine generators and superconducting magnetic energy storages. J Energy Storage 51:104356
73. Abdelrazek AS, El-Sehiemy RA, Rezk H, Ghoniem RM, Falaras P, Zaky AA (2022) Dynamic electrical models of perovskite solar cells considering hysteresis and charge accumulations effects by using equilibrium optimizer. IEEE Access 10:104111–104122
74. Ramadan A, Kamel S, Neggaz N, Alghamdi A (2022) Developing photovoltaic cells parameter estimation algorithm based on equilibrium optimization technique. J Eng Res. 10(4A)
75. Shaik MA, Mareddy PL, Visali N (2022) Enhancement of voltage profile in the distribution system by reconfiguring with dg placement using equilibrium optimizer. Alex Eng J 61(5):4081–4093
76. Cikan M, Kekezoglu B (2022) Comparison of metaheuristic optimization techniques including Equilibrium optimizer algorithm in power distribution network reconfiguration. Alex Eng J 61(2):991–1031
77. Houssein EH, Hassan MH, Mahdy MA, Kamel S (2022) Development and application of equilibrium optimizer for optimal power flow calculation of power system. Appl Intell. https://doi.org/10.1007/s10489-022-03796-7
78. Tran MQ, Elsisi M, Vu VQ, Albalawi F, Ghoneim SS (2022) Effective optimization based on equilibrium optimizer for dynamic cutting force coefficients of the end-milling process. Mathematics 10(18):3287
79. Aryan P, Raja GL (2022) A novel equilibrium optimized double-loop control scheme for unstable and integrating chemical processes involving dead time. Int J Chem Reactor Eng 20(12):1341–1360
80. Ahmadipour M, Othman MM, Alrifaey M, Bo R, Ang CK (2022) Classification of faults in grid-connected photovoltaic system based on wavelet packet transform and an equilibrium optimization algorithm-extreme learning machine. Measurement 197:111338
81. Houssein EH, Dirar M, Abualigah L, Mohamed WM (2022) An efficient equilibrium optimizer with support vector regression for stock market prediction. Neural Comput Appl. https://doi.org/10.1007/s00521-021-06580-9
82. Legoui KZ, Maza S, Attia A (2022, November) Equilibrium optimizer and henry gas solubility optimization algorithms for feature selection: comparison study. In 2022 5th International Symposium on Informatics and its Applications (ISIA). IEEE (pp. 1–6)
83. Chang GW, Chinh NC, Sinatra C (2022) Equilibrium optimizer-based approach of pv generation planning in a distribution system for maximizing hosting capacity. IEEE Access 10:118108–118122
84. Safa B, Rasouli A, Nasira Y (2022) A two-step damage diagnostic approach based on static strain energy and model-updating via the equilibrium optimizer. Shock Vib. https://doi.org/10.1155/2022/3792828
85. Abderazek H, Yildiz AR, Sait SM (2021) Optimization of constrained mechanical design problems using the equilibrium optimization algorithm. Materials Testing 63(6):552–559
86. Amiri S, Mosallanejad A, Sheikhahmadi A (2021) Medical images fusion based on equilibrium optimization and discrete wavelet. Int J Nonlinear Anal Appl 12(1):1337–1354
87. Behera S, Parida SS, Panda SK, Behera S (2021, September) Voltage control optimization by equilibrium optimizer for unity power factor operation of grid-connected three-phase photovoltaic inverter. In 2021 International Symposium of Asian Control Association on Intelligent Robotics and Industrial Automation (IRIA). IEEE. (pp. 209–214)
88. Hou C, Shi J, Zhang B (2021, December) Evolving Dendritic Neuron Model by Equilibrium Optimizer Algorithm. In 2021 IEEE International Conference on Progress in Informatics and Computing (PIC). IEEE (pp. 14–18)
89. Wu X, Hirota K, Tang B, Dai Y, Jia Z (2021) Ameliorated Frenet trajectory optimization method based on artificial emotion and equilibrium optimizer. J Adv Comput Intell Intell Inform 25(1):110–120
90. Abo El-Ela AA, Allam SM, Shaheen AM, Nagem NA (2021) Optimal allocation of biomass distributed generation in distribution systems using equilibrium algorithm. Int Transact Electr Energy Syst 31(2):e12727
91. Ndi FE, Perabi SN, Ndjakomo SE, Abessolo GO, Mengata GM (2021) Estimation of single-diode and two diode solar cell parameters by equilibrium optimizer method. Energy Rep 7:4761–4768
92. Rezk H, Aly M, Fathy A (2021) A novel strategy based on recent equilibrium optimizer to enhance the performance of PEM fuel cell system through optimized fuzzy logic MPPT. Energy 234:121267
93. Mansoor M, Mirza AF, Duan S, Zhu J, Yin B, Ling Q (2021) Maximum energy harvesting of centralized thermoelectric power generation systems with non-uniform temperature distribution based on novel equilibrium optimizer. Energy Convers Manage 246:114694
94. Abou El-Ela AA, El-Seheimy RA, Shaheen AM, Wahbi WA, Mouwafi MT (2021) PV and battery energy storage integration in distribution networks using equilibrium algorithm. J Energy Storage 42:103041
95. Dinh PH (2021) Multi-modal medical image fusion based on equilibrium optimizer algorithm and local energy functions. Appl Intell 51(11):8416–8431
96. Houssein EH, Nageh G, Abd Elaziz M, Younis E (2021) An efficient equilibrium optimizer for parameters identification of photovoltaic modules. PeerJ CompuT Sci 7:e708

97. Seleem SI, Hasanien HM, El-Fergany AA (2021) Equilibrium optimizer for parameter extraction of a fuel cell dynamic model. Renew Energy 169:117–128
98. Ngo PTT, Pham TD, Hoang ND, Tran DA, Amiri M, Le TT et al (2021) A new hybrid equilibrium optimized SysFor based geospatial data mining for tropical storm-induced flash flood susceptible mapping. J Environ Manag 280:111858
99. Hashem M, Abdel-Salam M, El-Mohandes MT, Nayel M, Ebeed M (2021) Optimal placement and sizing of wind turbine generators and superconducting magnetic energy storages in a distribution system. J Energy Storage 38:102497
100. Micev M, Ćalasan M, Oliva D (2021) Design and robustness analysis of an automatic voltage regulator system controller by using equilibrium optimizer algorithm. Comput Electr Eng 89:106930
101. Dinh PH (2021) Combining gabor energy with equilibrium optimizer algorithm for multi-modality medical image fusion. Biomed Signal Process Control 68:102696
102. Shaheen AM, Elsayed AM, El-Sehiemy RA, Abdelaziz AY (2021) Equilibrium optimization algorithm for network reconfiguration and distributed generation allocation in power systems. Appl Soft Comput 98:106867
103. Ismael OY, Qasim M, Noaman MN (2021) Equilibrium optimizer-based robust sliding mode control of magnetic levitation system. J Européen des Systèmes Automatisés 54(1):131–138
104. Dubey SM, Dubey HM, Pandit M, Salkuti SR (2021) Multi-objective scheduling of hybrid renewable energy system using equilibrium optimization. Energies 14(19):6376
105. Ahmed D, Ebeed M, Ali A, Alghamdi AS, Kamel S (2021) Multi-objective energy management of a micro-grid considering stochastic nature of load and renewable energy resources. Electronics 10(4):403
106. Soliman MA, Al-Durra A, Hasanien HM (2021) Electrical parameters identification of three-diode photovoltaic model based on equilibrium optimizer algorithm. IEEE Access 9:41891–41901
107. Al-akayshee AS, Kuznetsov ON, Sultan HM (2021, January) Application of equilibrium optimization algorithm for optimal design of PV/hydroelectric pumped storage energy system, Case Study–Iraq. In 2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus). IEEE (pp. 1354–1359)
108. Durmus A, Kurban R (2021) Optimum design of linear and circular antenna arrays using equilibrium optimization algorithm. Int J Microw Wirel Technol 13(9):986–997
109. Kharrich M, Kamel S, Abdeen M, Mohammed OH, Akherraz M, Khurshaid T, Rhee SB (2021) Developed approach based on equilibrium optimizer for optimal design of hybrid PV/wind/diesel/battery microgrid in Dakhla, Morocco. IEEE Access 9:13655–13670
110. Tikhe G, Tanvi J, Ashwin L, Aamod S, Jayaraman V (2021) Feature selection using equilibrium optimizer. In Data Engineering and Intelligent Computing: Proceedings of ICICC 2020. Springer, Singapore pp. 307–315
111. Premkumar M, Sowmya R, Jangir P, Nisar KS, Aldhaifallah M (2021) A new metaheuristic optimization algorithm for brushless direct current wheel motor design problem. Comput Mater Continua 67(2):2227–2242
112. Ahanch M, McCann R (2021, April) Integrated volt/var control and conservation voltage reduction in unbalanced distribution networks considering smart pv inverter control using equilibrium optimizer algorithm. In 2021 IEEE Kansas Power and Energy Conference (KPEC). IEEE. (pp. 1–6)
113. Nguyen TA, Pham DC, Thanh NC, Nguyen AN (2021) Implementation of equilibrium optimizer algorithm for MPPT in a wind turbine with PMSG. Wseas Transact Syst Control 16:216–223
114. Nguyen QT, Bui MP (2021) Performance of equilibrium optimizer for the traveling salesman problem. Int J Intell Eng Syst 14(5):46–55
115. Pandya SB, Jariwala HR (2021) Equilibrium optimizer: insights, balance, diversity for renewable energy resources based optimal power flow with multiple scenarios. Smart Sci 9(4):257–274
116. Sun F, Yu J, Zhao A, Zhou M (2021) Optimizing multi-chiller dispatch in HVAC system using equilibrium optimization algorithm. Energy Rep 7:5997–6013
117. Soliman MH, Talaat HE, Attia MA (2021) Power system frequency control enhancement by optimization of wind energy control system. Ain Shams Eng J 12(4):3711–3723
118. Roy B, Singh MP, Kaloop MR, Kumar D, Hu JW, Kumar R, Hwang WS (2021) Data-driven approach for rainfall-runoff modelling using equilibrium optimizer coupled extreme learning machine and deep neural network. Appl Sci 11(13):6238
119. Yang Q, Liang K, Su T, Geng K, Pan M (2021) Broad learning extreme learning machine for forecasting and eliminating tremors in teleoperation. Appl Soft Comput 112:107863
120. ElSayed SK, Al Otaibi S, Ahmed Y, Hendawi E, Elkalashy NI, Hoballah A (2021) Probabilistic modeling and equilibrium optimizer solving for energy management of renewable micro-grids incorporating storage devices. Energies 14(5):1373
121. Zayed ME, Zhao J, Li W, Elsheikh AH, Abd Elaziz M (2021) A hybrid adaptive neuro-fuzzy inference system integrated with equilibrium optimizer algorithm for predicting the energetic performance of solar dish collector. Energy 235:121289
122. Agnihotri S, Atre A, Verma HK (2020, February) Equilibrium optimizer for solving economic dispatch problem. In 2020 IEEE 9th Power India International Conference (PIICON). IEEE. (pp. 1–5)
123. Rabehi A, Nail B, Helal H, Douara A, Ziane A, Amrani M et al (2020) Optimal estimation of Schottky diode parameters using a novel optimization algorithm: Equilibrium optimizer. Superlattices Microstruct 146:106665
124. Abdul-hamied DT, Shaheen AM, Salem WA, Gabr WI, El-sehiemy RA (2020) Equilibrium optimizer based multi dimensions operation of hybrid AC/DC grids. Alex Eng J 59(6):4787–4803
125. Bastawy M, Ebeed M, Rashad A, Alghamdi AS, Kamel S (2020, November) Micro-grid dynamic economic dispatch with renewable energy resources using equilibrium optimizer. In 2020 IEEE Electric Power and Energy Conference (EPEC). IEEE. (pp. 1–5)
126. Nusair K, Alhmoud L (2020) Application of equilibrium optimizer algorithm for optimal power flow with high penetration of renewable energy. Energies 13(22):6066
127. Agwa AM (2020) Equilibrium optimization algorithm for automatic generation control of interconnected power systems. Przeglad Elektrotechniczny 96(9):143–148
128. Nguyen T, Nguyen G, Nguyen BM (2020) EO-CNN: an enhanced CNN model trained by equilibrium optimization for traffic transportation prediction. Procedia Comput Sci 176:800–809
129. Hemalatha R, Umamaheswari R, Jothi S (2021) LF distribution and equilibrium optimizer based fuzzy logic for multipath routing in MANET. Wireless Pers Commun 120(2):1837–1861
130. Elsheikh AH, Shehabeldeen TA, Zhou J, Showaib E, Abd Elaziz M (2021) Prediction of laser cutting parameters for polymethylmethacrylate sheets using random vector functional link network integrated with equilibrium optimizer. J Intell Manuf 32:1377–1388
131. Guha D, Roy PK, Banerjee S (2021) Equilibrium optimizer-tuned cascade fractional-order 3DOF-PID controller in load frequency control of power system having renewable energy resource integrated. Int Trans Electr Energ Syst 31(1):e12702

132. He B, Lin HC, Meng X, Liu W (2022, October) An improved equilibrium optimizer: dealing with economic emissions problem in power system dispatch. In 2022 IEEE Industrial Electronics and Applications Conference (IEACon).IEEE. (pp. 73–77)
133. Lan Z, He Q, Jiao H, Yang L (2022) An improved equilibrium optimizer for solving optimal power flow problem. Sustainability 14(9):4992
134. Gui P, He F, Ling BWK, Zhang D (2021) United equilibrium optimizer for solving multimodal image registration. Knowl-Based Syst 233:107552
135. Zhong C, Li G, Meng Z, Li H, He W (2023) A self-adaptive quantum equilibrium optimizer with artificial bee colony for feature selection. Comput Biol Med 2:106520
136. Houssein EH, Çelik E, Mahdy MA, Ghoniem RM (2022) Self-adaptive equilibrium optimizer for solving global, combinatorial, engineering, and multi-objective problems. Expert Syst Appl 195:116552
137. Li Y, Wang W, Liu J, Zhou H (2022) Equilibrium optimizer with divided population based on distance and its application in feature selection problems. Knowl-Based Syst 256:109842
138. Ansingkar NP, Patil RB, Deshmukh PD (2022) An efficient multi class Alzheimer detection using hybrid equilibrium optimizer with capsule auto encoder. Multimed Tools Appl 81(5):6539–6570
139. Das G, Panda R, Samantaray L, Agrawal S (2022) A novel non-entropic objective function for multilevel optimal threshold selection using adaptive equilibrium optimizer. Iran J Electr Electr Eng 18(2):2230–2230
140. Ahmed S, Ghosh KK, Mirjalili S, Sarkar R (2021) AIEOU: Automata-based improved equilibrium optimizer with U-shaped transfer function for feature selection. Knowl-Based Syst 228:107283
141. Wunnava A, Naik MK, Panda R, Jena B, Abraham A (2020) A novel interdependence based multilevel thresholding technique using adaptive equilibrium optimizer. Eng Appl Artif Intell 94:103836
142. Yehia M, Allam D, Zobaa AF (2022) A novel hybrid fuzzy-metaheuristic strategy for estimation of optimal size and location of the distributed generators. Energy Rep 8:12408–12425
143. Khadanga RK, Kumar A, Panda S (2021) Application of interval type-2 fuzzy PID controller for frequency regulation of ac islanded microgrid using modified equilibrium optimization algorithm. Arab J Sci Eng 46(10):9831–9847
144. Agrawal U, Rohatgi V, Katarya R (2022) Normalized mutual information-based equilibrium optimizer with chaotic maps for wrapper-filter feature selection. Expert Syst Appl 207:118107
145. Wang WY, Kang JT, Li K, Fan YH, Lin P (2022) A Novel intelligent inversion method of hydrogeological parameters based on the disturbance-inspired equilibrium optimizer. Sustainability 14(6):3267
146. Sayed GI, Khoriba G, Haggag MH (2022) A novel chaotic equilibrium optimizer algorithm with S-shaped and V-shaped transfer functions for feature selection. J Amb Intell Hum Comput. https://doi.org/10.1007/s12652-021-03151-7
147. Mousa AAA, El-Shorbagy MA, Mustafa I, Alotaibi H (2021) Chaotic search-based equilibrium optimizer for dealing with nonlinear programming and petrochemical application. Processes 9(2):200
148. Ates A (2021) Enhanced equilibrium optimization method with fractional order chaotic and application engineering. Neural Comput Appl 33(16):9849–9876
149. Lan P, Xia K, Pan Y, Fan S (2021) An improved equilibrium optimizer algorithm and its application in LSTM neural network. Symmetry 13(9):1706
150. Zheng-Ming G, Juan ZHA, Su-Ruo LI, Ru-Rong HU (2020, May). The improved equilibrium optimization algorithm with tent map. In 2020 5th international conference on computer and communication systems (ICCCS). IEEE (pp. 343–346)
151. Bardhan A, GuhaRay A, Gupta S, Pradhan B, Gokceoglu C (2022) A novel integrated approach of ELM and modified equilibrium optimizer for predicting soil compression index of subgrade layer of dedicated freight corridor. Transport Geotech 32:100678
152. Abdel-Basset M, Mohamed R, Mirjalili S, Chakrabortty RK, Ryan MJ (2021) MOEO-EED: A multi-objective equilibrium optimizer with exploration–exploitation dominance strategy. Knowl-Based Syst 214:106717
153. Tang AD, Han T, Zhou H, Xie L (2021) An improved equilibrium optimizer with application in unmanned aerial vehicle path planning. Sensors 21(5):1814
154. Gupta S, Deep K, Mirjalili S (2020) An efficient equilibrium optimizer with mutation strategy for numerical optimization. Appl Soft Comput 96:106542
155. Faramarzi A, Mirjalili S, Heidarinejad M (2022) Binary equilibrium optimizer: Theory and application in building optimal control problems. Energy Build 277:112503
156. Ouadfel S, Abd Elaziz M (2022) Efficient high-dimension feature selection based on enhanced equilibrium optimizer. Expert Syst Appl 187:115882
157. Varzaneh ZA, Hossein S, Mood SE, Javidi MM (2022) A new hybrid feature selection based on improved equilibrium optimization. Chemom Intell Lab Syst 228:104618
158. Minocha S, Singh B (2022) A novel phishing detection system using binary modified equilibrium optimizer for feature selection. Comput Electr Eng 98:107689
159. Zhang M, Wang JS, Hou JN, Song HM, Li XD, Guo FJ (2022) RG-NBEO: a ReliefF guided novel binary equilibrium optimizer with opposition-based S-shaped and V-shaped transfer functions for feature selection. Artif Intell Rev. https://doi.org/10.1007/s10462-022-10333-y
160. Minocha S, Singh B (2022) Band selection technique based on binary modified equilibrium optimizer for hyperspectral image classification. J Appl Remote Sens 16(4):048502
161. Haouassi H, Mahdaoui R, Chouhal O, Bakhouche A (2022) An efficient classification rule generation for coronary artery disease diagnosis using a novel discrete equilibrium optimizer algorithm. J Intell Fuzzy Syst. https://doi.org/10.3233/JIFS-213257
162. Mohamed B, Mohaisen L, Amin M (2022) Binary equilibrium optimization algorithm for computing connected domination metric dimension problem. Scientific Programm. https://doi.org/10.1155/2022/6076369
163. Hu P, Chu SC, Snášel V, Pan JS (2022) Binary equilibrium optimizer algorithm. J Netw Intell
164. Malik MM, Haouassi H (2022) Efficient sequential covering strategy for classification rules mining using a discrete equilibrium optimization algorithm. J King Saud University-Comput Inform Sci 34(9):7559–7569
165. Guha R, Ghosh KK, Bera SK, Sarkar R, Mirjalili S (2023) Discrete equilibrium optimizer combined with simulated annealing for feature selection. Journal of Computational Science 67:101942
166. Rahab H, Haouassi H, Laouid A (2022) Rule-based Arabic sentiment analysis using binary equilibrium optimization algorithm. Arab J Sci Eng. https://doi.org/10.1007/s13369-022-07198-2
167. Elmanakhly DA, Saleh MM, Rashed EA (2021) An improved equilibrium optimizer algorithm for features selection: methods and analysis. IEEE Access 9:120309–1203271

168. Abdel-Basset M, Mohamed R, Mirjalili S (2021) A binary equilibrium optimization algorithm for 0–1 knapsack problem. Comput Ind Eng 151:106946
169. Gao Y, Zhou Y, Luo Q (2020) An efficient binary equilibrium optimizer algorithm for feature selection. IEEE Access 8:140936–140963
170. Liu J, Li W, Li Y (2022) LWMEO: An efficient equilibrium optimizer for complex functions and engineering design problems. Expert Syst Appl 198:116828
171. Minocha S, Singh B (2022) A novel equilibrium optimizer based on levy flight and iterative cosine operator for engineering optimization problems. Expert Syst 39(2):e12843
172. Zhang J (2022) Levy equilibrium optimizer algorithm for the DNA storage code set. PLoS ONE 17(11):e0277139
173. Balakrishnan K, Dhanalakshmi R, Akila M, Sinha BB (2022) Improved equilibrium optimization based on Levy flight approach for feature selection. Evol Syst. https://doi.org/10.1007/s12530-022-09461-1
174. Mostafa A, Ebeed M, Kamel S, Abdel-Moamen MA (2021) Optimal power flow solution using levy spiral flight equilibrium optimizer with incorporating CUPFC. IEEE Access 9:69985–69998
175. Zhao J, Gao ZM (2020, May) The improved equilibrium optimization algorithm with Lévy flight. In 2020 5th International Conference on Computer and Communication Systems (ICCCS). IEEE (pp. 352–355)
176. Yi L, Li G, Chen K, Liu Q, Liu J (2022) Optimal scheduling of residential houses with optimal photovoltaic energy utilization strategy using improved multi-objective equilibrium optimizer algorithm. J Build Eng 59:105102
177. Abou El-Ela AA, El-Sehiemy RA, Shaheen AM, Wahbi WA, Mouwafi MT (2022) A multi-objective equilibrium optimization for optimal allocation of batteries in distribution systems with lifetime maximization. J Energy Storage 55:105795
178. Yi L, Li G, Chen K, Liu J, Fan L, Gao X (2022) Optimal scheduling of intelligent building with photovoltaic energy storage system using competitive mechanism integrated multi-objective equilibrium optimizer algorithm. Arab J Sci Eng. https://doi.org/10.1007/s13369-022-06831-4
179. Yu, B. C., & Shao, L. S. (2022). An optimization method of mine ventilation system based on R2 index hybrid multi-objective equilibrium optimization algorithm. Energy Reports, 8, 11003-11021.
180. Premkumar M, Jangir P, Sowmya R, Alhelou HH, Mirjalili S, Kumar BS (2022) Multi-objective equilibrium optimizer: framework and development for solving multi-objective optimization problems. J Comput Design Eng 9(1):24–50
181. El-Shorbagy MA, Mousa AA (2021) Constrained multiobjective equilibrium optimizer algorithm for solving combined economic emission dispatch problem. Complexity 2021:1–14
182. Abdel-Basset M, Mohamed R, Abouhawwash M (2021) Balanced multi-objective optimization algorithm using improvement-based reference points approach. Swarm Evol Comput 60:100791
183. Chen H, Li W, Cui W (2020) Disruption-based multi-objective equilibrium optimization algorithm. Comput Intell Neurosci. https://doi.org/10.1155/2020/8846250
184. Wang WY, Xu ZH, Fan YH, Pan DD, Lin P, Wang XT (2023) Disturbance inspired equilibrium optimizer with application to constrained engineering design problems. Appl Math Model 116:254–276
185. Shao ZY, Pan JS, Hu P, Chu SC (2021). Equilibrium optimizer of interswarm interactive learning strategy. Enterprise Information Systems, 1–25
186. Wu X, Hirota K, Jia Z, Ji Y, Zhao K, Dai Y (2023) Ameliorated equilibrium optimizer with application in smooth path planning oriented unmanned ground vehicle. Knowl-Based Syst 260:110148
187. Zhang X, Lin Q (2022) Information-utilization strengthened equilibrium optimizer. Artif Intell Rev 55:4241
188. Zhou Z, Yang X, Zhu Z, Wang Y, Liu D (2022) Color constancy with an optimized regularized random vector functional link based on an improved equilibrium optimizer. J Opt Soc Am A 39(3):482–493
189. Das G, Panda R, Samantaray L, Agrawal S (2022) A novel segmentation error minimization-based method for multilevel optimal threshold selection using opposition equilibrium optimizer. Int J Image Graph 2350021
190. Aswini J, Yamini B, Jatothu R, Nayaki KS, Nalini M (2022) An efficient cloud-based healthcare services paradigm for chronic kidney disease prediction application using boosted support vector machine. Concurr Comput: Practice Exp 34(10):e6722
191. Li Y, Liang X, Liu J, Zhou H (2022) Multi-strategy equilibrium optimizer: an improved meta-heuristic tested on numerical optimization and engineering problems. PLoS ONE 17(10):e0276210
192. Elgamal ZM, Yasin NM, Sabri AQM, Sihwail R, Tubishat M, Jarrah H (2021) Improved equilibrium optimization algorithm using elite opposition-based learning and new local search strategy for feature selection in medical datasets. Computation 9(6):68
193. Fan, Q., Huang, H., Yang, K., Zhang, S., Yao, L., & Xiong, Q. (2021). A modified equilibrium optimizer using opposition-based learning and novel update rules. Expert Systems with Applications, 170, 114575.
194. Dinkar SK, Deep K, Mirjalili S, Thapliyal S (2021) Opposition-based Laplacian equilibrium optimizer with application in image segmentation using multilevel thresholding. Expert Syst Appl 174:114766
195. Naik MK, Panda R, Abraham A (2021) An opposition equilibrium optimizer for context-sensitive entropy dependency based multilevel thresholding of remote sensing images. Swarm Evol Comput 65:100907
196. Shankar N, Saravanakumar N, Kumar C, Kamatchi Kannan V, Indu Rani B (2021) Opposition-based equilibrium optimizer algorithm for identification of equivalent circuit parameters of various photovoltaic models. J Comput Electron 20(4):1560–1587
197. Fu Z, Hu P, Li W, Pan JS, Chu S (2021) Parallel equilibrium optimizer algorithm and its application in capacitated vehicle routing problem. Intell Automat Soft Comput 27(1):233
198. Xu XW, Pan TS, Song PC, Hu CC, Chu SC (2021) Multi-cluster-based equilibrium optimizer algorithm with compact approach for power system network. J Netw Intell 6(1):117–142
199. Pan JS, Zhuang J, Liao L, Chu SC (2021) Advanced equilibrium optimizer for electric vehicle routing problem with time windows. J Netw Intell 6(2):216–237
200. Altantawy DA, Kishk SS (2023) Equilibrium-based COVID-19 diagnosis from routine blood tests: A sparse deep convolutional model. Expert Syst Appl 213:118935
201. Vommi AM, Battula TK (2023) A binary Bi-phase mutation-based hybrid equilibrium optimizer for feature selection in medical datasets classification. Comput Electr Eng 105:108553
202. Sun Y, Pan JS, Hu P, Chu SC (2022) Enhanced equilibrium optimizer algorithm applied in job shop scheduling problem. J Intell Manuf. 1–27
203. Eid A, Kamel S, Houssein EH (2022) An enhanced equilibrium optimizer for strategic planning of PV-BES units in radial distribution systems considering time-varying demand. Neural Comput Appl 34(19):17145–17173
204. Aval SBB, Mohebian P (2022) Joint damage identification in frame structures by integrating a new damage index with equilibrium optimizer algorithm. Int J Struct Stab Dyn 22(05):2250056

205. Rizk-Allah RM, Hassanien AE (2022) A hybrid equilibrium algorithm and pattern search technique for wind farm layout optimization problem. ISA transactions
206. Duan Y, Liu C, Li S, Guo X, Yang C (2023) An automatic affinity propagation clustering based on improved equilibrium optimizer and t-SNE for high-dimensional data. Inf Sci 623:434–454
207. Kumar A, Khadanga RK, Panda S (2022) Reinforced modified equilibrium optimization technique-based MS-PID frequency regulator for a hybrid power system with renewable energy sources. Soft Comput 26:5437
208. Dinh Pham T, Nguyen TT, Kien LC (2022) An Improved equilibrium optimizer for optimal placement of distributed generators in distribution systems considering harmonic distortion limits. Complexity 2022(11):774
209. Houssein EH, Helmy BED, Oliva D, Jangir P, Premkumar M, Elngar AA, Shaban H (2022) An efficient multi-thresholding based COVID-19 CT images segmentation approach using an improved equilibrium optimizer. Biomed Signal Process Control 73:103401
210. Yang L, Xu Z, Liu Y, Tian G (2022) An improved equilibrium optimizer with a decreasing equilibrium pool. Symmetry 14(6):1227
211. Zhu B, Luo Q, Zhou Y, Zhang Y, Yin S Optimal reactive power dispatch problem using an improved equilibrium optimizer. Available at SSRN 4063765
212. Nguyen NA, Nguyen TT, Duong TL (2022) An improved equilibrium optimizer algorithm for solving optimal power flow problem with penetration of wind and solar energy. Int Transact Electr Energy Syst
213. Ates A, Chen Y (2021, August) Fractional order chaotic model based enhanced equilibrium optimization algorithm for controller design of 3 DOF hover flight system. In International design engineering technical conferences and computers and information in engineering conference (Vol. 85437, p. V007T07A018). American Society of Mechanical Engineers
214. Sun R, Zhu X, Lin S, Zhu T, Wang J (2021) Optimal control design of VSC-HVDC systems integrated with offshore wind farm via enhanced equilibrium. The 10th renewable power generation conference (RPG 2021) pp. 69–704
215. Too J, Mirjalili S (2021) General learning equilibrium optimizer: a new feature selection method for biological data classification. Appl Artif Intell 35(3):247–263
216. Wang J, Yang B, Li D, Zeng C, Chen Y, Guo Z et al (2021) Photovoltaic cell parameter estimation based on improved equilibrium optimizer algorithm. Energy Convers Manag 236:114051
217. Zhao J, Gao ZM (2020, April). A random walk equilibrium optimization algorithm. In 2020 3rd International Conference on Advanced Electronic Materials, Computers and Software Engineering (AEMCSE). IEEE (pp. 22–25)
218. Abdel-Basset M, Mohamed R, Mirjalili S, Chakrabortty RK, Ryan MJ (2020) Solar photovoltaic parameter estimation using an improved equilibrium optimizer. Sol Energy 209:694–708
219. Sayed EA, Sameh MA, Attia MA, Badr AO (2023) Enhancement of PV performance by using hybrid TLBO-EO optimization. Ain Shams Eng J 14(3):101892
220. Wang X, Hu J, Hu J, Wang Y (2022) A modified equilibrium optimizer using opposition-based learning and teaching-learning strategy. IEEE Access 10:101408–101433
221. Tahernezhad-Javazm F, Rankin D, Coyle D (2022, July) R2-HMEWO: Hybrid multi-objective evolutionary algorithm based on the equilibrium optimizer and whale optimization algorithm. In 2022 IEEE Congress on Evolutionary Computation (CEC). IEEE (pp. 1–8)
222. Tan WH, Mohamad-Saleh J (2022) A hybrid whale optimization algorithm based on equilibrium concept. Alexandria Engineering Journal
223. Heidari E, Movaghar A, Motameni H, Barzegar B (2022) A novel approach for clustering and routing in WSN using genetic algorithm and equilibrium optimizer. Int J Commun Syst 35(10):e5148
224. Hemeida M, Senjyu T, Alkhalaf S, Fawzy A, Ahmed M, Osheba D (2022) Reactive power management based hybrid GAEO. Sustainability 14(11):6933
225. Bakry OM, Alhabeeb A, Ahmed M, Alkhalaf S, Senjyu T, Mandal P, Dardeer M (2022) Improvement of distribution networks performance using renewable energy sources-based hybrid optimization techniques. Ain Shams Eng J 13(6):101786
226. Yin S, Luo Q, Zhou Y (2022) EOSMA: an equilibrium optimizer slime mould algorithm for engineering design problems. Arab J Sci Eng 47(8):10115–10146
227. Yin S, Luo Q, Zhou G, Zhou Y, Zhu B (2022) An equilibrium optimizer slime mould algorithm for inverse kinematics of the 7-DOF robotic manipulator. Sci Rep 12(1):9421
228. Wei Y, Othman Z, Daud KM, Yin S, Luo Q, Zhou Y (2022) Equilibrium optimizer and slime mould algorithm with variable neighborhood search for job shop scheduling problem. Mathematics 10(21):4063
229. Swain M, Tripathy TT, Panda R, Agrawal S, Abraham A (2022) Differential exponential entropy-based multilevel threshold selection methodology for colour satellite images using equilibrium-cuckoo search optimizer. Eng Appl Artif Intell 109:104599
230. Chattopadhyay, S., Dey, A., Singh, P. K., Ahmadian, A., & Sarkar, R. (2023). A feature selection model for speech emotion recognition using clustering-based population generation with hybrid of equilibrium optimizer and atom search optimization algorithm. Multimedia Tools and Applications, 82(7), 9693–9726.
231. Makhadmeh SN, Al-Betar MA, Assaleh K, Kassaymeh S (2022) A hybrid white shark equilibrium optimizer for power scheduling problem based IoT. IEEE Access 10:132212–132231
232. Ćalasan M, Micev M, Radulović M, Zobaa AF, Hasanien HM, Abdel Aleem SH (2021) Optimal pid controllers for AVR system considering excitation voltage limitations using hybrid equilibrium optimizer. Machines 9(11):265
233. Jia H, Peng X (2021) High equilibrium optimizer for global optimization. J Intell Fuzzy Syst 40(3):5583–5594
234. Qi H, Zhang G, Jia H, Xing Z (2021) A hybrid equilibrium optimizer algorithm for multi-level image segmentation. Math Biosci Eng 18:4648–4678
235. Sayed A, Ebeed M, Ali ZM, Abdel-Rahman AB, Ahmed M, Abdel Aleem SH, El-Shahat A, Rihan M (2021) A hybrid optimization algorithm for solving of the unit commitment problem considering uncertainty of the load demand. Energies 14(23):8014
236. Hemalatha, R., Umamaheswari, R., & Jothi, S. (2021). ANFIS Based Optimal Routing using Group Teaching and Adaptive Equilibrium Optimization based Trust Aware Routing Protocol in MANET.
237. Dey A, Chattopadhyay S, Singh PK, Ahmadian A, Ferrara M, Sarkar R (2020) A hybrid meta-heuristic feature selection method using golden ratio and equilibrium optimization algorithms for speech emotion recognition. IEEE Access 8:200953–200970

238. Guha, R., Ghosh, K. K., Bera, S. K., Sarkar, R., & Mirjalili, S. (2023). Discrete equilibrium optimizer combined with simulated annealing for feature selection. Journal of Computational Science, 101942.
239. Rai R, Dhal KG, Das A, Ray S (2023) An Inclusive Survey on Marine Predators Algorithm: Variants and Applications. Arch Comput Methods Eng. https://doi.org/10.1007/s11831-023-09897-x
240. Rai R, Das A, Ray S, Dhal KG (2022) Human-inspired optimization algorithms: Theoretical foundations, algorithms, open-research issues and application for multi-level thresholding. Arch Comput Methods Eng. https://doi.org/10.1007/s11831-022-09766-z
241. Rai R, Das A, Dhal KG (2022) Nature-inspired optimization algorithms and their significance in multi-thresholding image segmentation: an inclusive review. Evol Syst 13(6):889–945
242. Dhal KG, Ray S, Rai R, Das A (2023) Archimedes optimizer: theory, analysis, improvements, and applications. Arch Comput Methods Eng. https://doi.org/10.1007/s11831-022-09876-8
243. Dhal KG, Das A, Ray S, Rai R, Ghosh TK (2022) Archimedes optimizer-based fast and robust fuzzy clustering for noisy image segmentation. J Supercomput 79(4):3691–730
244. Dhal KG., Rai R, Das A, Ghosh TK. (2023, January). Hybridization of sine-cosine algorithm with K-means for pathology image clustering. In Artificial Intelligence: First International Symposium, ISAI 2022, Haldia, India, February 17–22, 2022, Revised Selected Papers. Springer Nature Switzerland, Cham (pp. 76–86)
245. Dhal KG, Das A, Ray S, Gálvez J (2021) Randomly attracted rough firefly algorithm for histogram based fuzzy image clustering. Knowl-Based Syst 216:106814

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