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A new optimization meta-heuristic algorithm based on self-defense mechanism of the plants with three reproduction operators

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Abstract

In this paper, a new meta-heuristic algorithm is presented, which is a new bio-inspired optimization algorithm based on the self-defense mechanisms of the plants. In the literature, there are many published works, where the authors scientifically demonstrate that plants have self-defense mechanisms (coping strategies) and these techniques are used to defend themselves from predators, in this case herbivorous insects. The proposed algorithm considers as its basis the predator prey model proposed by Lotka and Volterra, which means that when the plant detects the presence of an invading organism, it triggers a series of chemical reactions, which products are emitted into the air to attract the natural predator of the invading organism. The performance of the proposed approach is verified with the optimization of a set of traditional benchmark mathematical functions and the CEC-2015 functions, and the results are compared statistically against other optimization meta-heuristics.

Keywords Self-defense of plants · Predator–prey models · herbivores · Levy flights

1 Introduction

Meta-heuristic algorithms have been very popular in recent years and are frequently used to solve optimization problems. There are many bio-inspired algorithms in the literature, such as PSO (particle swarm optimization) (Higashitani et al. 2006; Kennedy 2011), ABC (artificial bee colony) (Karaboga and Basturk 2007; Kıran and Fındık 2015; Teodorovic 2009), ACO (ant colony optimization) (Azar et al. 2016; Neyoy et al. 2013), GA (genetic algorithm) and GSA (gravitational search algorithm). These optimization algorithms have been applied to many problems, for example optimization of neural networks and fuzzy logic. For example in Johanyák and Papp (2012), Neyoy et al. (2013), Neyoy et al. (2013) and Precup et al. (2014), fuzzy logic is used to adapt some parameters of bio-inspired algorithms, for greater performance and stability. There is also algorithm hybridization to solve multiple optimization problems such as routing, function approximation and route optimization. In this paper, a new meta-heuristic optimization algorithm is proposed. The proposed optimization algorithm is based on the self-defense mechanisms of the plants. The main goal of this proposal is to explore and exploit new meta-heuristic processes that help us solve different problems and compete against traditional algorithms that have already been studied and exploited. The main idea is to create an alternative that can be able to solve complex problems reducing time and computational cost. In the literature, some authors have demonstrated that plants are living organisms that comply with biological physiological processes such as respiration and reproduction, carrying a complex life cycle using different reproduction methods such as pollination and graft . This reproduction processes are used to generate populations of new individuals that reach maturity or may repeat the same cycle, and so on, to avoid the extinction of their species and their predators (Tollsten and Muller 1996; Vivanco et al. 2005). In Caraveo et al. (2015a) and Duffy et al. (2003), the authors have published previous works using the basic ideas of this optimization algorithm applied to the optimization of benchmark mathematical functions for different numbers of dimensions and using different reproduction methods, published results showing that the performance of the algorithm is efficient even being a new algorithm and is in the development stage and improvements (Caraveo et al. 2015b).

The main contribution in this work is the creation of a new optimization algorithm based on self-defense mechanisms of

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the plants, and in addition, different methods of biological reproduction are also developed as part of this algorithm. In this case, the predator–prey model proposed by Lotka and Volterra is used as the basis for this new proposed algorithm. The main difference of this algorithm with respect to the prey–predator model is that the proposed algorithm has an evolutionary process, where plants develop coping strategies to survive from predators and also have different methods for biological reproduction to conserve this species. In addition, each reproduction method considers different characteristics of the plant to reproduce.

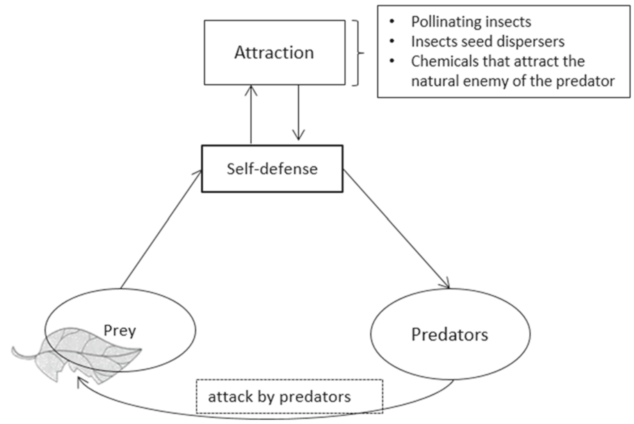

Fig. 1 General scheme of the predator attack on plants

2 Related work

In the literature, there are some published works where the authors use the predatory–prey model, to model problems, but the main difference of our proposal against the existing works is that we propose an optimization algorithm, which is iterative and applying evolution processes to improve the adaptation to the habitat that it belongs. Neyoy et al. (2013) applied the traditional predator prey model to approximate the solution of nonlinear functions; also in Yoshida et al. (2003), the predatory–prey method is used as a prediction model, which would be used in ecology if the evolution of the species were in shorter time cycles. Duan et al. (2013) performed a hybridization of the algorithms of BSO and predator–prey, to control a DC brushless motor. Brain storm optimization (BSO) is a newly developed swarm intelligence optimization algorithm inspired by a human being's behavior of brainstorming. In Heil and Ton (2008), a case study is presented, about the method of reproduction by grafting in plants. Caraveo et al. (2015b) and Rhoades (1985) propose a new optimization algorithm bio-inspired in the self-defense mechanisms of plants applied to benchmark mathematical functions. The previous above-mentioned work is the one that can be considered most similar to the work proposed in this paper.

2.1 Self-defense of the plants

Defense mechanisms (or coping strategies) are automatic natural processes that protect individuals against external or internal threats in general. In nature, plants are exposed to many invading predators, such as insects, fungi, bacteria and virus (Bennett and Wallsgrove 1994; Berryman 1992; Cruz and González 2008; Pieterse and Dicke 2007). Plants do not have mobility; therefore, their survival depends entirely on their immune system and other strategies or evolutionary adaptation strategies developed to prevent death or extinction of the plants (Laumanns et al. 1998; Paré and Tumlinson 1999; Pieterse and Dicke 2007; Rhoades 1985; Ryan and Jagendorf 1995). This suggests that the defense mechanisms of the plants are very effective to lock or counteract an infection and keep away predators. Additionally, it has been shown that plants are able to react to different stimuli (Wolfe 2000), such as light intensity, quantity and quality of water or the presence of some toxic substances around. Plants have a linear behavior pattern, which acts directly to any external stimulus. When the plant suffers from aggression, it triggers a series of chemical reactions that release substances into the air, which attract the predator's natural enemies that are attacking the plant (Law and Regnier 1971; Ordeñana 2002; Paré and Tumlinson 1999; Ryan and Jagendorf 1995; Wang and Metzlaff 2005; Wolfe 2000). In Fig. 1, a general diagram of the plant defense process when it detects the presence of an invading organism is presented.

In Fig. 1, a general diagram of the self-defense process of the plant is presented for when it detects the attack by a predator, for example insects, bacteria and fungi (Duffy et al. 2003; García-Garrido and Ocampo 2002). In this case, a plant releases a series of chemical reactions and the products are released into the air; this attracts different types of insects, such as pollinating insects to achieve the reproduction before death and preserve their species against extinction. These can also be insects like seed dispensers, or the natural enemy of the predator that is attacking the plant. In nature, the plants have different methods of biological reproduction, for example pollination, graft and cloning, these are some of the most common methods of reproduction, and the methods are described in more detail below:

Graft A method of vegetative reproduction of plants, where a portion of tissue extracted from a plant is inserted into another, in order that both grow as a single organism and share their features (Heil and Ton 2008). The graft method of reproduction is possible only between species of plants belonging to the same species, so that their tissues can be compatible and ensure the survival of the species, and this method is illustrated in Fig. 2.

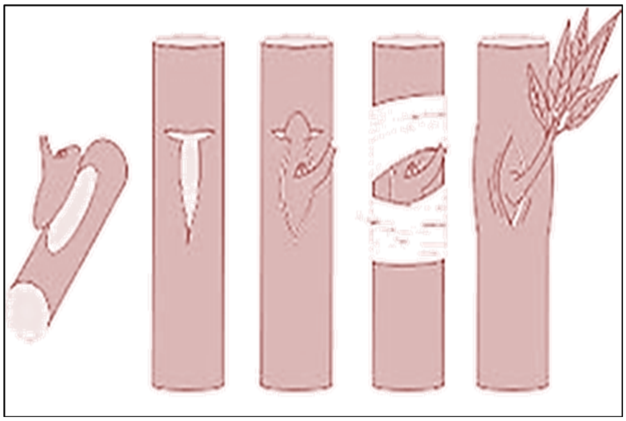

Fig. 2 Biological reproduction method graft

In Fig. 2, we find a graphical representation of the graft method of vegetative reproduction, where a fragment is taken from one plant and inserted into another plant and that automatically starts a process of merging between the two tissues to grow as a single plant and inheriting their different characteristics.

Cloning In a biological sense, cloning is realized by obtaining genetically identical individuals. Also in nature, there are clones; from the descendants of those organisms that reproduce asexually, plants can be propagated from a fragment of the plant. This method of biological reproduction allows the best plants or individuals to reproduce and preserve their characteristics, which are then inherited to other generations. Figure 3 illustrates the cloning process.

In Fig. 3, an illustration of the reproductive cloning method is presented, and this method allows providing the next generation the best genes and characteristics of plants that can be preserved throughout time.

Pollination Pollination is a biological reproduction method used by plants to send grains of pollen from one plant (flower) to another plant (flower). In order for this process to be performed, it depends on several factors, and in this case the most common are:

Pollination by insects (biotic) This process of reproduction is totally dependent on birds and insect pollinators; in fact, pollination is more common using bees; when a bee visits a plant to collect honey, it also collects pollen and this pollen is transported to the following plants the bee visits on its way in search for food. This process is also performed by other insects such as butterflies, bats, ants and other animals (Yang 2012, 2009; Yoshida et al. 2003). In Fig. 4, we can find an illustration of the process of pollination by insects, where an insect randomly decides to visit neighboring plant.

Pollination by air (abiotic) In this case, the pollen produced by plants is transported to other locations using air currents, and in this case the air is totally responsible for carrying the pollen from one flower to another flower (Yang 2012).

3 The predator prey model

The Lotka–Volterra equations, also known as the predator–prey equations, are a pair of first-order, nonlinear, differential equations frequently used to describe the dynamics of biological systems in which two species interact, one as the predator and the other as the prey. The populations change through time according to the following pair of equations (Berryman 1992; Caraveo et al. 2015b; Xiao and Chen 2001):

$$\frac{dx}{dt} = \alpha x - \beta x y \tag{1}$$

$$\frac{dy}{dt} = -\delta x y + \lambda y \tag{2}$$

Equation (1) represents the population growth of plants in the absence of predators. Equation (2) represents the decrease in predator population in the absence of plants at time t.

where

x : is the number of prey (for example, plants)
y is the number of some type of predator (for example, insects)
$\frac{dx}{dt}$ and $\frac{dy}{dt}$ represent the growth rates of the two populations over time
t : represents time

α: Represents the birth rate of plants in the absence of predators
β: Represents the death rate of predators in the absence of plants.
δ: Measures the susceptibility of plants.
λ: Measures the ability of predation.

4 Proposed method

In this paper, we propose a new optimization method, which is bio-inspired on the self-defense process of plants in nature. This new algorithm is created with the aim of solving complex optimization problems with a minimal computer use and reducing runtime of the algorithm. For the development of the proposed algorithm, the predator prey model proposed by Lotka–Volterra was used as the main theoretical basis. As explained in Sect. 2, plants are able to react to different stimuli, such as air, sun, water, darkness and threats by different predators, such as providing shelter for other animals to protect them from different predators that feed on them (Berryman 1992; Caraveo et al. 2015a). In Fig. 4, we find in more details on the procedure that the algorithm performs internally in the proposed approach.

The description of the stages and operations of the algorithm is presented in Table 1

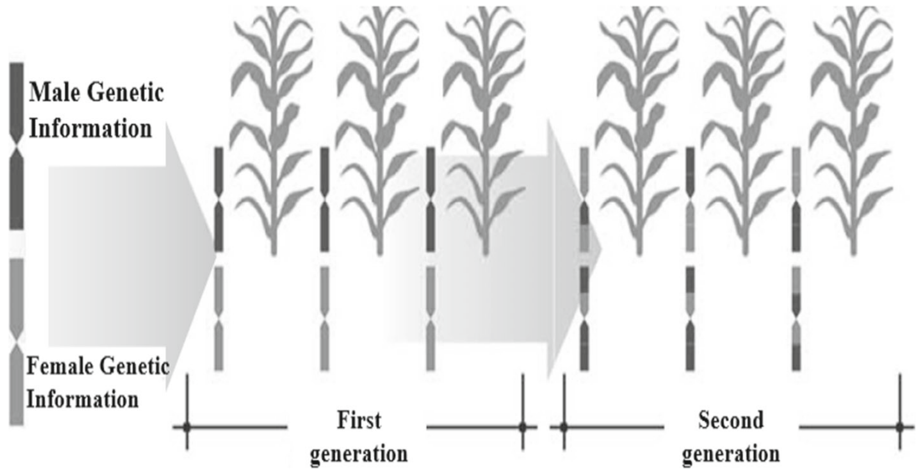

Fig. 3 Biological reproduction cloning method

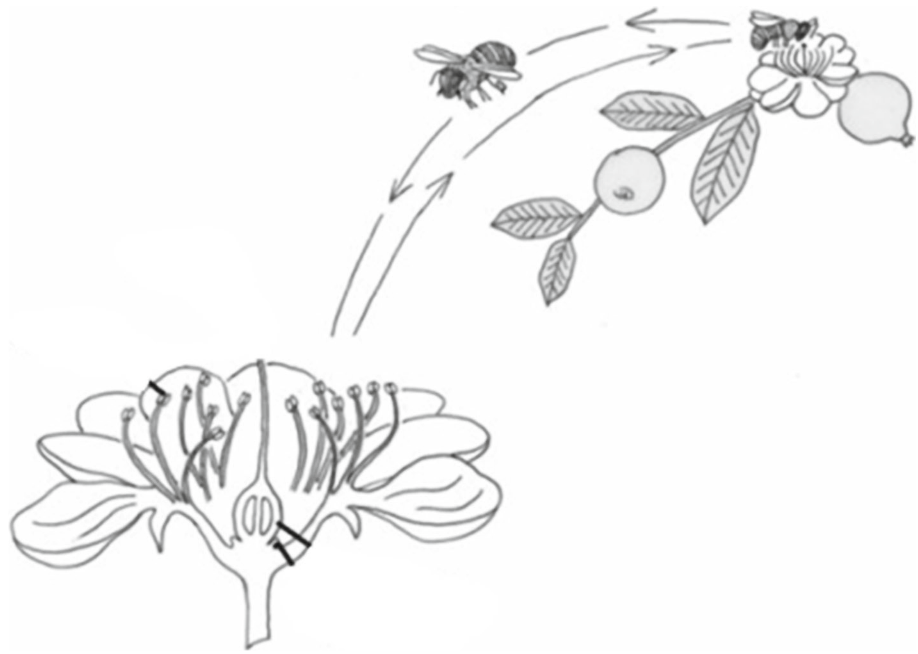

Fig. 4 Reproduction method by pollination

In Fig. 5, a general diagram of the algorithm and operations is presented; also the biological representation of the reproduction used in this proposal is presented.

In Fig. 6, an illustration is presented, where we can observe the traditional predator prey model and the approach proposed by the authors in this work, and as we can notice, we are focusing on the population of prey. In this case, plants are subject of an evolution process, to develop their confrontation techniques, and for this process it is necessary to apply some biological operators as shown in Fig. 6.

4.1 Biological reproduction method and proposed approach

This section describes in more detail the internal representation of the reproduction methods, in the proposed algorithm.

Reproduction method by the graft process in this case, a stem of a plant is used in another plant to generate an alteration of its structure.

In the previous session, the method of reproduction by graft was described, this method is one of the most used, and it allows us to preserve the best characteristics of an individual and inherit to the future generations of new plants. In Fig. 7, a general diagram of the process performed in nature and the internal process of the algorithm (our proposal) is presented. The plant with higher fitness value of the population is obtained, and then, a second plant is taken from the population, in this case one of the plants with a low fitness value. Both plants are combined to improve the characteristics of the plant with lower fitness value, with a probability $p(x) \in [0, 1]$, and a local or global graft is determined. A global graft consists in inserting some of the best

Table 1 Description and performed operations by the proposed meta-heuristic

Step	Description
Start	The algorithm begins
Initialize parameters	The α, β, λ, δ parameters must be initialized before starting the algorithm, and these parameters help control the growth of both populations in the absence of prey or predators. Also other factors, such as the amount of food that can be consumed and the number of confrontations between the two populations, defined the reproduction method to use, such as graft, pollinated and clone
Plants and predators	In this step, these two populations interact with each other and the initial population of plants is generated
Initial populations	After each encounter between prey and predator, a plant population is generated
Evaluate the fitness of each plant	In this step, a pre-evaluation is performed to detect the fitness value of each plant, and the characteristics of the plant can be inherited to another plant, according to the reproduction method used
Reproduction operators	In this phase of the algorithm, the biological reproduction operator is applied, and in this case we only consider three operators: reproduction by cloning, graft and pollination, when the algorithm started the user manually selects the preproduction method to use
Select the best fitness from each plant	In this step of the algorithm, all plants are evaluated using a method of selection; in this case, we use the roulette selection type, and of this population, the best plants are selected to replace the worst plants in the new populations generated by the encounters between the two species
Iter $>$ iter$_{max}$	In this step, a condition is verified to validate whether the maximum number of iterations is complete; otherwise it returns to step number 4 and continues with the iterations
end	End the search process of the algorithm

characteristics of the plant in all the subpopulation, and a local graft consists in inserting characteristics of the best plant only in another plant; it is also called a local search and global search, all this with the purpose of maintaining a better balance between exploitation and exploration in the proposed algorithm. In the following paragraph, the method of biological reproduction by pollination is described.

Reproduction method by the Pollination process The transport of pollen is performed by air or by animals. The plants produce millions of grains of pollen that are transported to other plants in the air. In the case of animals, the plants attract insects and birds using flower colors, producing nectar, or producing volatile pollen that is transported by air, and in Fig. 8 a representation of the natural process and the proposal is presented.

In Fig. 8, a general diagram is presented of the process performed in nature and the process of the proposed method, the plant with greater fitness value, is selected to pollinate other plants as shown; then, a second plant is taken from the population.

In this case, the plant with higher fitness value is used to pollinate neighboring plants, with a probability $p(x) \in [0, 1]$; then, it is determined whether the pollinating insect visits plants that have lower or higher distance from its current value; for this reproduction method, we are using as a basis the Levy flights (Waser et al. 1996; Yang 2010) as shown in Fig. 9.

Lévy flights, named in honor of French mathematician Paul Pierre Lévy, are a type of random walk where the length of the jumps is distributed according to a probability of distribution (Yang 2009, 2012). In this case for each pollinator insect, a Levy flight is assigned and the length of the pollinating insect flight is determined with a certain probability, this in order to maintain a better balance between exploitation and exploration in the proposed algorithm. Next the reproduction by cloning method is described (Fig. 10).

Reproduction by the cloning method process The cloning method is a method used to preserve the total characteristics of an individual; in this case, this method is used to preserve the plant with greater fitness value of the population and inherit all the characteristics in the new offspring. In Fig. 10, a general diagram of the original approach and proposed approach is presented.

In Fig. 10, we can find a general scheme of the natural process and internal process of the proposed algorithm. In this case, during the iterations of the algorithm the fitness value of each plant is measured, and the plant with a low fitness value is cloned with the characteristics of the plant with greater fitness value, with a probability $p(x) \in [0, 1]$; it is determined whether to apply a local or global cloning.

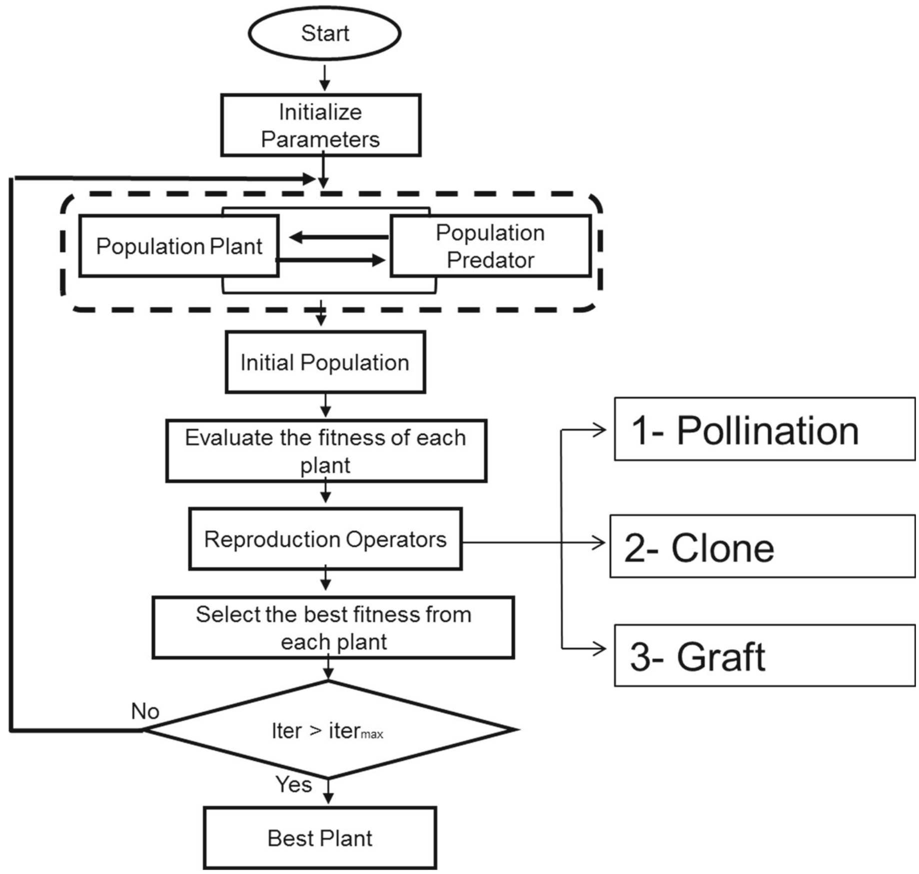

Fig. 5 Flowchart of the proposed approach

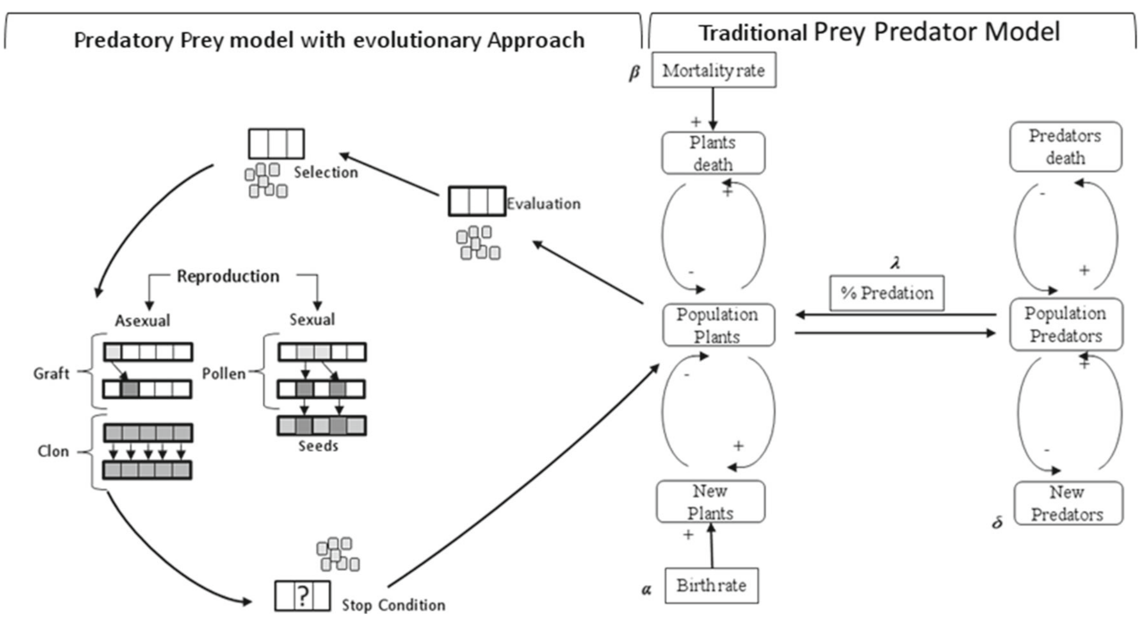

Fig. 6 General illustration of the proposal

5 Case study

The performance of the proposed algorithm is tested on the benchmark mathematical functions listed below (Johanyák and Papp 2012; Neyoy et al. 2013; Yang 2010). The name and the mathematical definition of the functions used in this work are shown below:

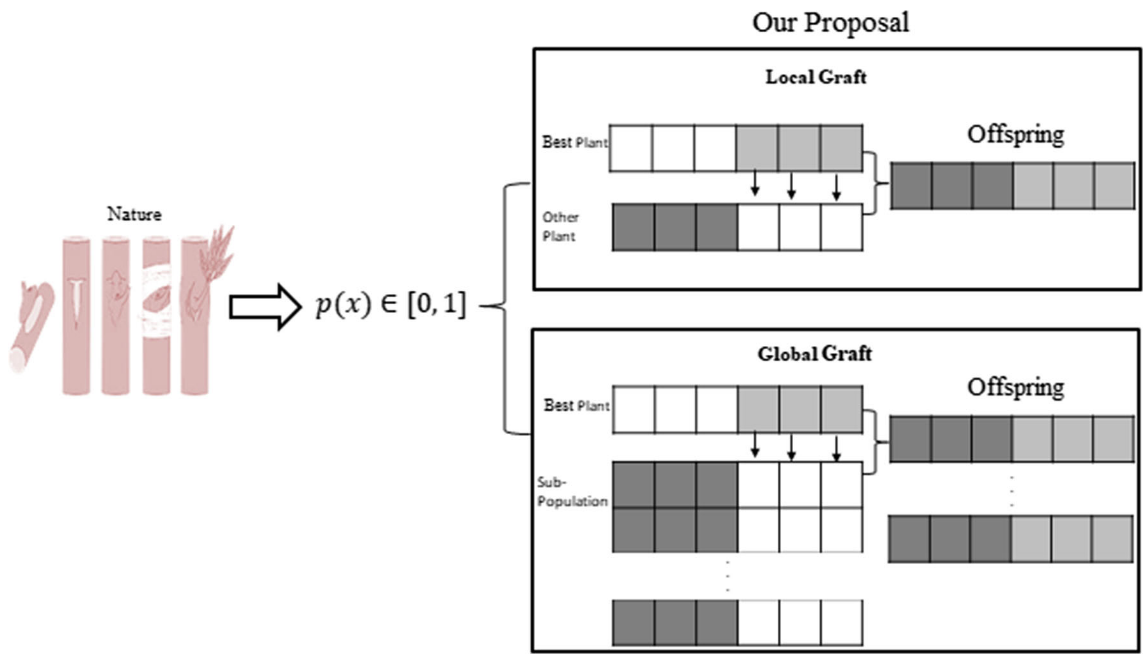

Fig. 7 Graft reproduction method

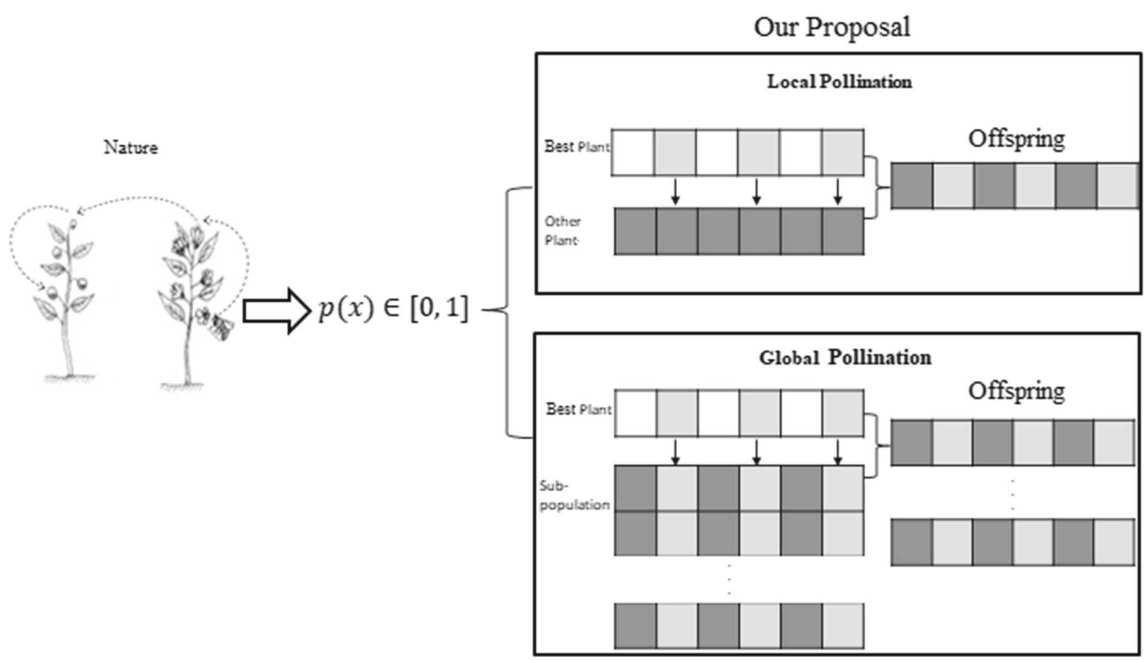

Fig. 8 Pollination reproduction method

5.1 Powell function

The function is usually evaluated on the hypercube $x_i \in [-4, 5]$, for all $i = 1, \dots, d$.

$$f(x) = \sum_{i=1}^{d/4} \Big[(x_{4i-3} + 10x_{4i-2})^2 + 5(x_{4i-1} - x_{4i})^2 + (x_{4i-2} - 2x_{4i-1})^4 + 10(x_{4i-3} - x_{4i})^2 \Big] \quad (3)$$

5.2 Ackley function

The function is usually evaluated on the hypercube $x_i \in [-32.768, 32.768]$, for all $i = 1, \ldots, d$, although it may also be restricted to a smaller domain.

$$f(x) = -a \cdot \exp\left(-b \cdot \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2) - \exp(\frac{1}{n}\sum_{i=1}^{n}\cos(cx_i)) + a + \exp(1)} \tag{4}$$

5.3 Griewank function

The function is usually evaluated on the hypercube $x_i \in [-600, 600]$, for all $i = 1, \ldots, d$.

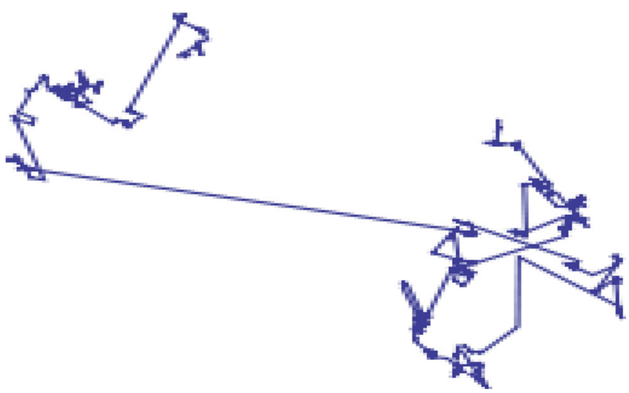

Fig. 9 Levy flight illustration

$$f(x) = \sum_{i=1}^{d} \frac{x_i^2}{4000} - \prod_{i=1}^{d} \cos\left(\frac{x_i}{\sqrt{i}}\right) + 1 \tag{5}$$

5.4 Rastrigin function

The function is usually evaluated on the hypercube $x_i \in [-5.12, 5.12]$, for all $i = 1, \ldots, d$.

$$f(x) = 10d + \sum_{i=1}^{d} [x_i^2 - 10\cos(2\pi x_i)] \tag{6}$$

5.5 Sphere function

The function is usually evaluated on the hypercube $x_i \in [-5.12, 5.12]$, for all $i = 1, \ldots, d$.

$$f(x) = \sum_{i=1}^{n} x_i^2 \tag{7}$$

5.6 Levy function

The function is usually evaluated on the hypercube $x_i \in [-10, 10]$, for all $i = 1, \ldots, d$.

$$f(x) = \sin^2(\pi\omega_1) + \sum_{i=1}^{d-1} (\omega_1 - 1)^2[1 + \sin^2(\pi\omega_i + 1)] + (\omega_d - 1)^2[1 + \sin^2(2\pi\omega_d)] \tag{8}$$

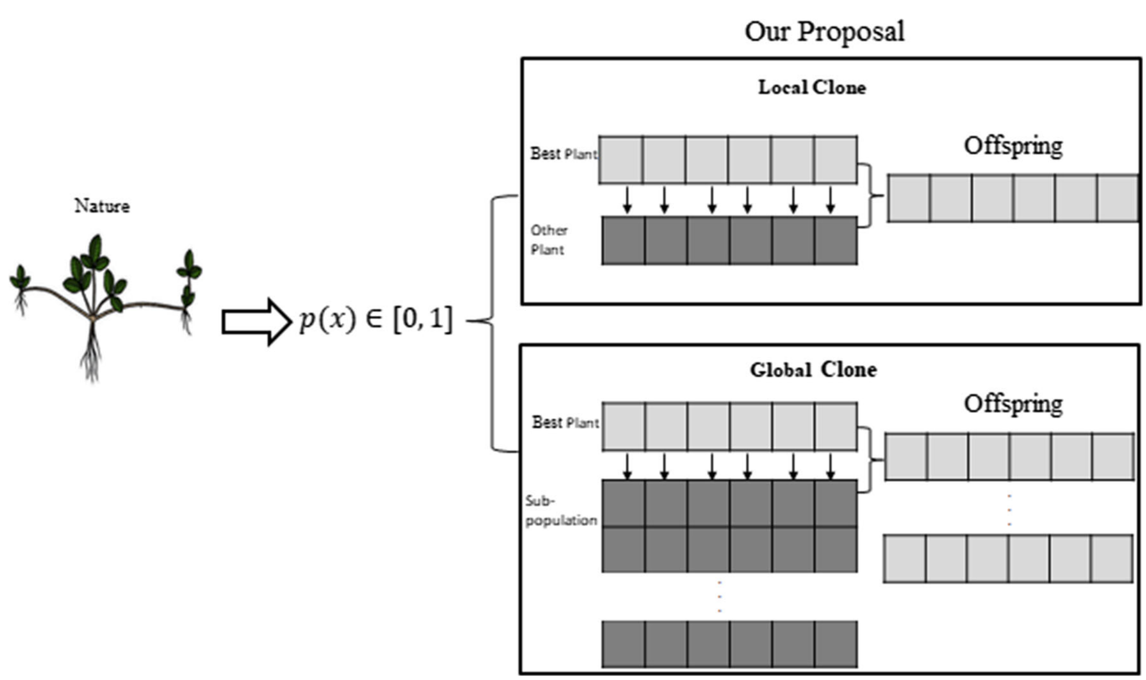

Fig. 10 Reproduction method by Cloning

5.7 Sum squares function

The function is usually evaluated on the hypercube $x_i \in [-10, 10]$, for all $i = 1, \ldots, d$, although this may be restricted to the hypercube $x_i \in [-5.12, 5.12]$, for all $i = 1, \ldots, d$.

$$f(x) = \sum_{i=1}^{n} i x_i^2 \tag{9}$$

5.8 Rotated hyper-ellipsoid function

The function is usually evaluated on the hypercube $x_i \in [-65.536, 65.536]$, for all $i = 1, \ldots, d$.

$$f(x) = \sum_{i=1}^{d} \sum_{j=1}^{1} x_j^2 \tag{10}$$

5.9 Dixon–Price function

The function is usually evaluated on the hypercube $x_i \in [-10, 10]$, for all $i = 1, \ldots, d$.

$$f(x) = (x_1 - 1)^2 + \sum_{i=2}^{d} i(2x_i^2 - x_{i-1})^2 \tag{11}$$

5.10 Zakharov function

The function is usually evaluated on the hypercube $x_i \in [-5, 10]$, for all $i = 1, \ldots, d$.

$$f(x) = \sum_{i=1}^{d} x_i^2 + \left(\sum_{i=1}^{d} 0.5 i x_i\right)^2 + \left(\sum_{i=1}^{d} 0.5 i x_i\right)^4 \tag{12}$$

6 Simulations

The optimization algorithm is bio-inspired on the self-defense mechanisms of plants, which was initially tested in optimizing benchmark mathematical functions, for the case study described on the previous section. It was tested for a set of 10 mathematical functions, for *30, 50 and 100* dimensions, where the objective value is approximating to zero. The initial sizes of both populations (plants, predators) are defined by the user, the parameters ($\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\lambda}$, $\boldsymbol{\delta}$) are also defined by the user, and for the model of Lotka and Volterra the following parameter values are recommended $\alpha = 0.4$, $\beta = 0.37$, $\lambda = 0.3$, $\delta = 0.05$. For this problem, the values for the variables are manually moved in the following ranges α, β, λ and δ and they are in [0, 1], with the purpose of observing the behavior of the algorithm, and determine what values and what ranges are optimal for the proposed algorithm, and the obtained results are shown in Table 2.

In Table 2, we can find the results after applying the algorithm to the mathematical functions proposed in this work. In this paper, we decided to show the most significant data for the 30 experiments performed using different methods of reproduction and different numbers of dimensions. The most significant data are: *functions, reproduction method, dimensions, best, worst, σ, average*. We can notice that the proposed approach demonstrates good performance in some of the proposed functions in this case study, such as *Dixon, Rosenbrock and Levy*. In these functions, the algorithm performance was low for some numbers of dimensions, but it is observed that when the number of dimensions is high, the algorithm has difficulty to approximate the value of the function to zero. In some experiments, the algorithm achieved very good results but not in others, and this behavior of the algorithm causes a standard deviation value and average very high results. The proposed algorithm is under improvements and adaptations in order to compete against existing algorithms in the literature, with the experiment ranges we find optimal values for the algorithm for this problem. The ranges of the dimensions are as follows: $\alpha = [0.3-0.7]$, $\beta = [0.1-0.4]$, $\lambda = [0.2-0.3]$, $\delta = [0.01-0.05]$, and for these ranges of values found for the dimensions, the algorithm offers us greater stability and balance in the exploration of solutions for this case study.

6.1 Statistical comparison

In summary, in this work we needed to perform the statistical comparison between the performances of the different methods of biological reproduction used in the proposed algorithm. In this statistical comparison, we consider only two methods in the comparison which are the more efficient according to the criteria of the experts. The statistical test used for the comparison is the Z test, whose parameters are defined in Table 3. We applied the statistical test for the case study shown in this paper, giving the following results shown in Table 4. In applying the statistical Z test, with a confidence level of 95%, the alternative hypothesis states that the average of the method of reproduction by pollination is lower than the average of the method of reproduction by graft, and of course the null hypothesis tells us that the average of the method of reproduction by pollination is greater than or equal to the average of the method of reproduction by graft, with a rejection region for all values that fall below level of -1.645. With a Z value of -20.696, we can conclude that the pollination reproductions method is more efficient than the method of reproduction by graft. For the function of the sphere and in Table 4, the statistical results for all the functions used in this work are shown.

Table 2 Experimental results for 30, 50 and 100 dimensions

Functions	Reprod. method	Dimensions	Best	Worst	σ	Average
Sphere	Pollination	30	1.77E−36	6.73E−15	1.23E−15	2.93E−16
		50	3.15E−76	5.92E−13	1.08E−13	1.98E−14
		100	2.49E−89	1.05E−24	2.21E−25	5.79E−26
	Clone	30	2.16E−43	6.415180	1.832414	0.709209
		50	2.1E−162	12.13978	4.729409	3.009083
		100	4.7E−205	42.73954	9.050110	2.728051
	Graft	30	4.6E−277	7.51464	1.473169	0.524378
		50	2.21E−67	0.92936	0.287375	0.136370
		100	1.25E−71	0.83502	0.245027	0.115840
Ackley	Pollination	30	8.88E−16	7.54E−14	1.67E−14	5.27E−14
		50	8.88E−16	1.21E−13	2.03E−14	9.14E−14
		100	4.89E−12	0.096420	0.018775	0.004928
	Clone	30	8.88E−16	0.881812	0.237640	0.154707
		50	8.88E−16	0.679788	0.211417	0.133736
		100	8.88E−16	3.487716	0.877724	0.325331
	Graft	30	3.19E−90	32.09056	7.669544	0.138961
		50	3.31E−16	2.915703	1.147050	0.896195
		100	6.51E−54	724.7575	1.247546	0.943876
Rastrigin	Pollination	30	2.27E−20	0.000488	8.92E−05	1.62E−05
		50	0	0.170530	0.031133	0.005688
		100	0	1.13E−12	3.928E−13	4.88E−13
	Clone	30	0	28.02403	5.255146	1.750358
		50	0	14.03068	3.252023	1.573388
		100	0	13.84076	3.887058	2.715852
	Graft	30	0	0.723871	0.229009	0.155026
		50	0	0.820359	0.211544	0.110639
		100	0	0.957874	0.344052	0.388034
Griewank	Pollination	30	0	0.010177	0.001858	0.000339
		50	0	0.0155	0.002831	0.000517
		100	0	0.008011	0.001462	0.000267
	Clone	30	0	0.251355	0.045857	0.011854
		50	0	0.331116	0.084452	0.036599
		100	0	0.395976	0.092751	0.029499
	Graft	30	0	1.028922	0.198676	0.073713
		50	0	0.878538	0.166315	0.052049
		100	0	1.090982	0.211168	0.091268
Powell	Pollination	30	3.88E−48	0.001196	0.000219	5.34E−05
		50	7.34E−33	0.002363	0.000454	0.000138
		100	1.07E−26	0.012232	0.002971	0.001125
	Clone	30	2.89E−54	17.62272	4.464192	1.961976
		50	4.43E−97	14.55935	3.523362	1.320921
		100	2.21E−72	2.466369	0.634546	0.395370
	Graft	30	1.12E−93	0.967712	0.243042	0.120675
		50	3.37E−67	6.751616	1.428210	0.530652
		100	5.91E−113	0.938540	0.378009	0.282427

Table 2 continued

Functions	Reprod. method	Dimensions	Best	Worst	σ	Average
Rosenbrock	Pollination	30	1.9187	28.71735	8.618153	19.58295
		50	13.6763	111.4038	13.81014	44.69458
		100	14.5684	116.545	14.25647	45.6587
	Clone	30	1.91872	28.71735	8.61815	19.58295
		50	13.6763	111.4038	13.81014	44.69458
		100	14.3776	111.4661	14.46581	48.6644
	Graft	30	1.91872	28.7173	8.618153	19.58295
		50	0.79570	44.93570	15.54095	35.36125
		100	2.0711	29.836	9.23035	17.74190
Sum square	Pollination	30	3.97E−130	1.50E−100	3.3E−101	1.0E−101
		50	4.38E−109	1.174E−73	2.55E−74	8.41E−75
		100	3.28E−93	1.543E−47	2.83E−48	6.68E−49
	Clone	30	0.017	0.0774	0.018171	0.047073
		50	0.0248	0.9359	0.280534	0.4549
		100	0.1498	3.8847	1.037645	2.55095
	Graft	30	3.19E−90	8.12853	1.561559	0.483303
		50	3.31E−16	28.3503	5.295961	1.706496
		100	6.51E−54	6.12060	1.314545	0.574652
Zakharov	Pollination	30	9.23E−50	3.90E−20	7.11E−21	1.48E−21
		50	2.33E−48	1.62E−10	3.90E−11	1.43E−11
		100	2.58E−77	0.103878	0.02099	0.00545
	Clone	30	0.0039	0.9575	0.29827	0.46026
		50	0.014	0.9135	0.25343	0.48358
		100	0.0918	2.9355	0.75097	1.39391
	Graft	30	3.13E−16	0.013715	0.00297	0.00076
		50	1.73E−14	0.9132	0.24840	0.10617
		100	3.342E−13	0.7469	0.16604	0.06018
Hyper	Pollination	30	1.82E−158	7.49E−51	1.42E−51	3.55E−52
		50	1.06E−137	8.48E−36	1.62E−36	3.86E−37
		100	2.82E−121	1.61E−23	4.04E−24	1.08E−24
	Clone	30	0.0002	0.0095	0.002113	0.00445
		50	0.0235	0.9688	0.309161	0.51737
		100	0.0145	1.9986	0.608632	1.06511
	Graft	30	3.67E−91	1.3364	0.387834	0.30489
		50	5.69E−106	9.2512	2.159921	1.06361
		100	1.13E−38	38.9208	9.614367	4.64223
Levy	Pollination	30	0.001473	1.36153	0.343047	0.11711
		50	0.008944	1.18304	0.304007	0.14539
		100	0.062205	8.90276	2.065917	1.11298
	Clone	30	0.189020	3.23484	0.843312	0.76403
		50	1.67E−05	0.94790	0.297364	0.31374
		100	0.03603	0.99425	0.407219	0.49375
	Graft	30	0.13535	3.25722	1.100443	0.95391
		50	0.30798	3.81686	1.502540	1.75416
		100	0.60231	6.88429	1.888266	2.20147

Table 2 continued

Functions	Reprod. method	Dimensions	Best	Worst	σ	Average
Dixon	Pollination	30	0.6666	1.58570	0.167768	0.69743
		50	0.6666	4.88802	0.770709	0.80738
		100	0.00481	0.66671	0.121197	0.64198
	Clone	30	0.5160	6.05080	0.972015	1.25908
		50	0.0113	0.9819	0.296911	0.41073
		100	0.0284	1.1959	0.324379	0.51037
	Graft	30	0.2898	5.9931	1.433557	1.52608
		50	0.1856	18.2151	4.847751	3.00834
		100	0.96215	30.8223	5.678660	3.36568

Table 3 Parameters for the statistical Z test

Parameters	Values
Confidence level	95%
Alpha	0.05
Ha	$\mu_1 < \mu_2$
H0	$\mu_1 \geq \mu_2$
Critical value	− 1.645

Table 4 Results of the z statistical test

Function name	Reproduction method		Z-value	Evidence
Ackley	Pollinations	Graft	−5.7692	Significant
Rastrigin			−6.3908	Significant
Sphere			−20.696	Significant
Griewank			−3.2290	Significant
Powell			−5.0589	Significant
Hyper			−12.187	Significant
Levy			−32.796	Significant
Dixon			−32.480	Significant
Zakharov			−0.4170	Not significant
Sum square			−19.105	Significant
Rosenbrock			−0.3872	Not significant

Table 5 Results of different meta-heuristics

Functions	Dimensions	GA	PSO	FPA	Our proposal
Ackley	25	8.29E−09	7.12E−12	5.09e−12	2.0221E−14
Sphere	25	6.61E−15	1.18E−24	2.47e−26	2.9397E−16
Griewank	25	5.72E−09	4.69E−09	1.37e−11	0.00033926
Rastrigin	25	2.93E−06	3.44E−06	4.52e−7	1.62962E−05
Rosenbrock	25	8.97E−06	8.21E−08	6.19e−8	19.5829600
Zakharov	25	8.77e−4	1.58e−4	9.53e−5	1.4873E−21

Analyzing the results shown in statistical test, we can notice that the method of reproduction by pollination is more efficient compared with the others for this problem. However, the other proposed methods on some number of iterations found many values near to the minimum values of the function and therefore are efficient, but not the best for this problem. In the previous statistical test, we can find that for the three proposed reproduction methods in this work, the best so far is reproduction by pollination using Levy flights.

In the previous statistical test, we can find that for the three proposed reproduction methods in this work, the best so far is reproduction by pollination using Levy flights. We also consider important to compare the results obtained with our proposal against other studies published in the literature, such as Yang et al. (2014) FPA (flower pollination algorithm), and the results published by the algorithm authors are shown in Table 5.

Table 5 shows the means of the results obtained using the different meta-heuristics of optimization, and we can note that the means of our proposal have managed to compete and be successful in some mathematical functions; it is important to mention that the authors (Yang et al. 2014) do not show enough information of the results to make a statistical comparison. However, we can conclude that the results obtained using the self-defense algorithm of the plants with reproduction by pollination have achieved acceptable results for this case study.

The performance of the proposed optimization metaheuristic was also tested with the benchmark functions of CEC 2015 (Laumanns et al. 1998). Based on previous publications, the authors recommend using the method of pollination as a reproduction operator, because it has a higher performance. In this test, 30 experiments were performed for the following mathematical functions of Table 6. The evaluation is for 10, 30 variables; for more information of the functions, please review (Laumanns et al. 1998). The main objective of this work is the proposal of a new optimization algorithm that can be used to solve multiple optimization problems.

In Tables 7 and 8, we can observe the results of 30 experiments for each function, using 10 and 30 dimensions; we

Table 6 Mathematical functions

Type	No.	Function
Unimodal	F1	Rotated high conditioned elliptic function
Functions	F2	Rotated cigar function
Simple	F3	Shifted and rotated Ackley's function
Multimodal	F4	Shifted and rotated Rastrigin's function
Functions	F5	Shifted and rotated Schwefel's function
Hybrid	F6	Hybrid function 1 ($N = 3$)
Functions	F7	Hybrid function 2 ($N = 4$)
	F8	Hybrid function 3 ($N = 5$)

Table 7 Results for 10 dimensions

Function	Important results of the algorithm			
	Best	Worse	σ	Average
F1	4.95E+04	4.38E+06	1.06E+06	1.03E+06
F2	1.40E+05	2.87E+06	7.45E+05	1.15E+06
F3	2.00E+01	2.04E+01	1.08E−01	2.03E+01
F4	8.08E+00	6.67E+01	1.67E+01	2.69E+01
F5	2.45E+02	1.08E+03	2.07E+02	6.24E+02
F6	3.55E+02	4.75E+04	8.66E+03	5.93E+03
F7	1.42E+00	1.23E+01	1.96E+00	2.89E+00
F8	9.41E+02	6.75E+03	1.34E+03	2.30E+03

Table 8 Results for 30 dimensions

Function	Important results of the algorithm			
	Best	Worse	σ	Average
F1	2.80E+06	2.94E+07	6.77E+06	1.199E+07
F2	1.74E+07	7.07E+09	1.34E+09	4.275E+08
F3	2.02E+01	2.10E+01	1.58E−01	2.09E+01
F4	1.62E+02	2.99E+02	3.90E+01	2.132E+02
F5	2.67E+03	5.54E+03	7.77E+02	3.91E+03
F6	3.57E+02	4.86E+04	8.82E+03	5.14E+03
F8	2.67E+04	1.18E+06	2.29E+05	2.22E+05

consider important to the reader the following information: the worse, best, average and standard deviation values.

We can observe that in the experiments it was very difficult to approximate the value of the function to zero. The mathematical functions used are very complex, some are hybrid, multimodal and composite, and this increases the complexity, and therefore, the algorithms have to be more efficient to be able to solve those functions.

To conclude this case study, it is necessary to make a statistical comparison against other published results; the test used is z-test. In Table 9, we can observe the parameters used in this test, and the results obtained with the algorithm of the mechanisms of the plants (MSPA) are compared with iterative hybridization of DE with local search for the CEC'2015 Special Section Large Scale Global Optimization (IHDELS) (Molina and Herrera 2015).

Table 9 Parameters for statistical comparison

Parameters	Values
Confidence level	95%
Alpha	0.05
Ha	$\mu_1 < \mu_2$
H0	$\mu_1 \geq \mu_2$
Critical value	− 1.645

Table 10 Results of applying the statistical Z test for 30 D

Case study	Our method	IHDELS	Z-value	Evidence
F1	MSPA	IHDELS	9.521	Not significant
F2			1.7474	Not significant
F3			19.8598	Not significant
F4			− 13.1429	Significant
F5			− 23.5751	Significant
F6			− 43.48	Significant
F7			− 14.8355	Significant

In applying the statistical Z-test, with a confidence level of 95%, the alternative hypothesis says that the average of the proposed method is lower than the average of IHDELS (Molina and Herrera 2015), and of course the null hypothesis tells us that the average of the proposed method is greater than or equal to the average of IHDELS (Molina and Herrera 2015), with a rejection region for all values fall below of − 1.645. In Table 10, we can observe the results of the statistical comparison

In the table, the statistical results of the proposed method are presented, where the success is observed in some functions presented in comparison with respect to the algorithm of differential evolution (DE) (Molina and Herrera 2015).

7 Conclusions

In this paper, we propose a new optimization meta-heuristic that is bio-inspired on the self-defense mechanisms of plants. This algorithm was created recently, and we have successfully achieved the integration of the predator prey model to the optimization algorithm, and consequently, we adapted some of the commonly methods most used in natural biological reproduction; in this case, the authors are considered to use graft, clone, and pollination using the Levy flights method. The three reproduction methods show acceptable results, and therefore, our proposal exceeds the expectations of the creators of the optimization algorithm. The main objective was to create a stable and efficient algorithm that is able to solve different optimization problems, in order to compete against different existing optimization methods in the literature. We should mention that we found optimal ranges of values for $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\lambda}$, $\boldsymbol{\delta}$ parameters, for this problem, and also for the mathematical functions of the CEC-2015, the proposal shows an acceptable performance. In this paper, the main contribution was the creation of a new optimization algorithm bio-inspired on the self-defense mechanisms of the plants in nature, with the integration of the predator–prey model and the development of different methods of biological reproduction as internal operators of the proposed algorithm.

Compliance with ethical standards

Conflict of interest All the authors in the paper 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.

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