An Innovative Hybrid Method Combining Grey Wolf and Marine Predator Optimization Techniques for Global and Constrained Problem Solving

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Abstract

The Grey Wolf Optimizer (GWO) is a meta-heuristic algorithm recognized for its effectiveness; however, it faces several limitations, such as a lack of diversity in its population, a tendency to prematurely converge on local optima, and insufficient convergence speed. To address these issues, we propose an innovative hybrid algorithm that combines the advantages of GWO with the Marine Predator Algorithm (MPA), leading to the creation of the Hybrid Grey Wolf Marine Predator Algorithm (HGWMPA). By integrating the adaptive characteristics of MPA, this hybrid approach fosters a robust search mechanism that effectively balances exploration and exploitation. We performed comprehensive experimental assessments utilizing benchmark functions from the CEC competitions of 2014, 2017, 2020, and 2022. The findings indicate that the HGWMPA consistently surpasses numerous leading optimization methods, achieving an average rank of 1 across most benchmark functions. Specifically, HGWMPA secured top positions in 76.67% of functions in the CEC 2014 test suite, 70.00% in CEC 2017, 90.00% in CEC 2020, and 66.67% in CEC 2022, showcasing its robust performance across various benchmark scenarios. The experimental results reveal that HGWMPA excels in global exploration, local exploitation, convergence speed, and accuracy, achieving optimal or near-optimal solutions with minimal standard deviations. A detailed performance evaluation, employing the Wilcoxon rank-sum test and the MARCOS MCDM ranking technique, further confirms the competitive advantages of HGWMPA. The algorithm's adaptability, characterized by the dynamic adjustment of parameters, enables an effective balance between exploration and exploitation, making it particularly suitable for a wide range of engineering design problems. Sensitivity analyses indicate that changes in population size, maximum iteration, and other parameter limits significantly influence the algorithm's performance, providing valuable insights for enhancing their configurations. HGWMPA has been successfully applied to diverse engineering design challenges, demonstrating its versatility and effectiveness in minimizing costs while adhering to critical design constraints. This advancement in optimization techniques, represented by HGWMPA, integrates pioneering concepts from both GWO and MPA to effectively tackle real-world challenges.

Keywords: Grey Wolf Optimizer, Marine Predator Algorithm, Hybrid Optimization, Exploration and Exploitation, Constrained Engineering Design.

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1. Results

1.1. Performance Evaluation

In this subsection, we present the results obtained from a thorough evaluation of the HGWMPA across various benchmark test suites, specifically CEC 2014, CEC 2017, CEC 2020, and CEC 2022. The findings are systematically organized in tables that facilitate direct comparison between HGWMPA and several established optimization algorithms, including the GWO [9], ACO [2], QIO [12], BBO [11], SCA [7], DMOA [1], SCSO [10], SSA [8], PSO [6], HS [4], MPA [3], and COA [5].

For each benchmark function, we provide essential performance metrics, such as average performance values (AVG), standard deviations (STD), and ranks (RANK). These metrics are crucial for understanding the effectiveness and reliability of HGWMPA in tackling complex optimization problems. The average performance values reflect the typical outcomes of the algorithms over multiple iterations, offering insight into their general effectiveness. In contrast, the standard deviations indicate the variability of the results, thereby illustrating the consistency of each optimization method.

Furthermore, the ranks assigned to each algorithm provide a comparative perspective on how HGWMPA performs relative to its peers. By analyzing these metrics, we can conclude the robustness and efficiency of the HGWMPA in solving intricate optimization challenges, showcasing its potential advantages in real-world applications.

1.1.1. Performance on CEC 2014

The performance results of the HGWMPA on the CEC-2014 test suite are presented in Tables 1 and 2. These tables provide a detailed comparison of HGWMPA against various established optimization algorithms across 30 benchmark functions, evaluated based on average values (AVG), standard deviations (STD), and ranks (RANK).

The initial group of functions, which includes F1, F2, and F3, demonstrates HGWMPA's outstanding performance. For Function F1, the algorithm achieved an average value of $1.0000E+02$ with a remarkably low standard deviation of $3.3671E-07$, securing the top rank among all tested algorithms. This result emphasizes HGWMPA's effectiveness in accurately identifying optimal solutions. In Function F2, HGWMPA maintained its leading position with an average of $2.0000E+02$ and a standard deviation of $1.3663E-05$, again ranking first. This consistency indicates that the algorithm is well-suited for functions requiring precise optimization. Function F3 further showcased HGWMPA's capabilities, achieving an average of $3.0000E+02$ and an impressive standard deviation of $3.7205E-10$, solidifying it as the top-performing method in this group.

The next set of functions, F4 to F16, presented more complex optimization challenges; however, HGWMPA continued to perform admirably. For Function F4, the algorithm achieved an average of $4.1057E+02$ and secured a rank of 2, indicating strong performance despite the increased difficulty. In Function F5, HGWMPA recorded an average of $5.2008E+02$ and ranked 6th, showcasing its versatility across diverse functions. As the complexity increased, Functions F6 through F16 tested the algorithm's adaptability and resilience. Notably, for Function F6, HGWMPA secured the top rank with an average of $6.0091E+02$. The algorithm maintained competitive performance in Functions F7 to F10, with ranks ranging from 1 to 4. For example, in Function F9, the average was $9.0634E+02$ with a rank of 1, while for Function F10, HGWMPA produced an average of $1.0649E+03$ and secured a rank of 2.

The performance of HGWMPA in the subsequent group of functions, F17 to F22, continues to illustrate its effectiveness in tackling complex optimization challenges. For Function F16, HGWMPA achieved an average value of $1.6021E+03$ with a standard deviation of $5.0796E-01$, again securing the top rank. This indicates not only its capability to find

Table 1: **Comparative Performance of HGWMPA on the CEC 2014 Test Suite (Dimensionality: 30)**

Function	Value	HGWMPA	GWA	QIO	ACO	BBO	SCA	DMOA	SCSO	SSA	PSO	HS	MPA	COA
F1	AVG	1.0000E+02	7.1072E+06	3.3811E+03	1.9918E+05	3.0174E+05	8.3983E+06	1.2403E+06	8.3250E+06	6.9801E+05	5.8362E+04	1.1408E+06	1.0000E+02	1.0315E+06
	STD	3.3671E-07	3.8904E+06	6.4357E+03	2.9660E+05	6.6773E+05	3.2110E+06	7.9791E+05	7.4446E+06	5.5248E+05	6.0463E+04	1.1743E+06	8.1092E-06	1.0792E+06
	RANK	1	11	3	5	6	13	10	12	7	4	9	1	8
F2	AVG	2.0000E+02	7.8578E+07	2.0960E+02	6.3995E+03	3.4571E+03	7.9911E+08	8.0488E+03	6.4845E+07	2.6920E+03	1.9950E+03	2.4679E+03	2.0000E+02	9.9742E+03
	STD	1.3663E-05	1.9152E+08	2.3920E+01	4.0259E+03	2.8330E+03	4.1536E+08	1.5678E+04	1.6890E+08	2.6988E+03	2.5509E+03	2.5695E+03	2.4153E-05	1.5303E+04
	RANK	1	12	3	8	7	13	9	11	6	4	5	2	10
F3	AVG	3.0000E+02	1.0669E+04	3.0075E+02	8.3034E+03	4.9591E+03	5.7899E+03	1.0397E+04	7.0698E+03	6.2740E+03	1.3513E+03	6.0117E+03	3.0000E+02	7.3677E+03
	STD	3.7205E-10	4.4363E+03	2.2745E+00	5.6067E+03	5.3671E+03	2.7961E+03	5.2892E+03	4.1560E+03	3.1552E+03	1.2256E+03	3.8412E+03	9.3467E-11	4.4989E+03
	RANK	1	13	3	11	5	6	12	9	8	4	7	1	10
F4	AVG	4.1057E+02	4.3839E+02	4.2267E+02	4.3478E+02	4.1992E+02	4.6531E+02	4.0399E+02	4.3949E+02	4.2848E+02	4.2498E+02	4.2440E+02	4.1072E+02	4.2019E+02
	STD	1.3689E+01	2.2142E+01	1.6233E+01	1.7568E-13	2.1164E+01	2.1069E+01	1.9314E+00	2.4810E+01	1.2963E+01	1.5269E+01	1.5522E+01	1.4876E+01	1.6696E+01
	RANK	2	11	6	10	4	13	1	12	9	8	7	3	5
F5	AVG	5.2008E+02	5.2046E+02	5.1985E+02	5.2040E+02	5.2000E+02	5.2035E+02	5.2037E+02	5.2012E+02	5.1875E+02	5.2031E+02	5.2015E+02	5.2001E+02	5.2006E+02
	STD	3.4889E-02	9.1646E-02	3.2632E+00	1.0008E-01	4.0439E-03	4.4537E-01	7.3551E-02	8.4930E-02	4.8795E+00	1.0542E-01	1.7319E-01	1.2579E-02	4.6997E-02
	RANK	6	13	2	12	3	10	11	7	1	9	8	4	5
F6	AVG	6.0091E+02	6.0249E+02	6.0162E+02	6.0174E+02	6.0360E+02	6.0754E+02	6.0698E+02	6.0584E+02	6.0347E+02	6.0110E+02	6.0219E+02	6.0091E+02	6.0570E+02
	STD	9.0082E-01	1.1338E+00	1.1757E+00	1.4783E+00	1.6556E+00	1.2033E+00	1.5188E+00	1.9454E+00	1.7602E+00	1.1260E+00	9.4545E-01	2.2177E-01	2.4852E+00
	RANK	1	7	4	5	9	13	12	11	8	3	6	2	10
F7	AVG	7.0009E+02	7.0244E+02	7.0009E+02	7.0051E+02	7.0011E+02	7.1264E+02	7.0020E+02	7.0272E+02	7.0025E+02	7.0013E+02	7.0005E+02	7.0005E+02	7.0042E+02
	STD	4.7297E-02	6.1745E+00	5.8069E-02	8.7633E-02	6.2488E-02	3.5579E+00	1.1452E-01	2.8971E+00	1.4527E-01	6.1119E-02	3.5947E-02	3.5616E-02	1.4355E-01
	RANK	3	11	4	10	5	13	7	12	8	6	2	1	9
F8	AVG	8.0445E+02	8.1214E+02	8.1065E+02	8.2853E+02	8.1167E+02	8.4184E+02	8.0981E+02	8.3326E+02	8.2379E+02	8.1148E+02	8.0000E+02	8.0292E+02	8.1815E+02
	STD	1.5831E+00	6.8500E+00	5.4693E+00	4.8436E+00	6.0432E+00	7.3076E+00	5.1661E+00	1.0685E+01	1.0379E+01	5.0715E+00	3.7595E-06	1.4765E+00	1.0562E+01
	RANK	3	8	5	11	7	13	4	12	10	6	1	2	9
F9	AVG	9.0634E+02	9.1714E+02	9.1347E+02	9.3117E+02	9.1874E+02	9.4541E+02	9.2266E+02	9.3612E+02	9.2531E+02	9.1612E+02	9.0924E+02	9.0932E+02	9.4524E+02
	STD	3.2767E+00	6.5574E+00	6.7821E+00	4.0843E+00	7.5729E+00	8.0779E+00	6.8770E+00	1.0972E+01	9.6276E+00	6.4449E+00	3.9426E+00	3.3409E+00	9.0238E+00
	RANK	1	6	4	10	7	13	8	11	9	5	2	3	12
F10	AVG	1.0649E+03	1.3993E+03	1.2299E+03	1.0921E+03	1.3685E+03	2.0231E+03	1.9630E+03	1.6611E+03	1.6286E+03	1.2779E+03	1.0002E+03	1.0865E+03	1.8626E+03
	STD	5.5304E+01	3.1885E+02	1.5821E+02	4.7673E+01	2.0017E+02	1.8911E+02	2.8657E+02	2.3098E+02	2.6960E+02	1.3468E+02	9.1006E-02	6.0166E+01	3.8248E+02
	RANK	2	8	5	4	7	13	12	10	9	6	1	3	11
F11	AVG	1.6158E+03	1.9212E+03	1.7341E+03	3.0379E+03	2.0229E+03	3.0524E+03	2.9877E+03	1.8849E+03	2.0863E+03	1.8796E+03	1.6933E+03	1.6556E+03	1.9778E+03
	STD	2.2292E+02	5.0170E+02	1.9159E+02	2.1434E+02	3.5485E+02	3.0288E+02	1.9361E+02	2.4910E+02	3.1666E+02	3.2563E+02	2.2880E+02	2.1178E+02	2.3596E+02
	RANK	1	7	4	12	9	13	11	6	10	5	3	2	8
F12	AVG	1.2001E+03	1.2009E+03	1.2009E+03	1.2013E+03	1.2001E+03	1.2013E+03	1.2013E+03	1.2004E+03	1.2003E+03	1.2001E+03	1.2001E+03	1.2000E+03	1.2005E+03
	STD	7.3597E-02	6.3730E-01	4.5523E-01	2.0482E-01	1.0125E-01	2.9974E-01	2.7627E-01	2.2906E-01	2.4120E-01	1.1700E-01	9.9843E-02	3.3415E-02	2.2169E-01
	RANK	3	9	10	12	4	13	11	7	6	5	2	1	8
F13	AVG	1.3001E+03	1.3002E+03	1.3002E+03	1.3002E+03	1.3003E+03	1.3007E+03	1.3002E+03	1.3004E+03	1.3004E+03	1.3001E+03	1.3002E+03	1.3001E+03	1.3003E+03
	STD	3.0663E-02	6.1503E-02	8.6261E-02	4.7605E-02	1.5605E-01	1.4537E-01	3.7776E-02	1.7330E-01	1.8896E-01	6.9203E-02	7.8819E-02	4.3407E-02	1.3302E-01
	RANK	1	5	8	6	9	13	4	12	11	3	7	2	10
F14	AVG	1.4001E+03	1.4005E+03	1.4003E+03	1.4002E+03	1.4003E+03	1.4012E+03	1.4003E+03	1.4004E+03	1.4003E+03	1.4002E+03	1.4003E+03	1.4002E+03	1.4003E+03
	STD	4.5315E-02	8.9807E-01	1.3893E-01	4.6564E-02	1.5655E-01	4.4566E-01	4.8063E-02	2.2220E-01	1.8721E-01	5.0142E-02	1.1830E-01	4.7979E-02	2.0563E-01
	RANK	1	12	6	4	9	13	5	11	8	3	7	2	10
F15	AVG	1.5008E+03	1.5021E+03	1.5014E+03	1.5027E+03	1.5021E+03	1.5095E+03	1.5024E+03	1.5214E+03	1.5018E+03	1.5010E+03	1.5010E+03	1.5009E+03	1.5031E+03
	STD	2.5678E-01	9.4127E-01	7.1779E-01	3.7391E-01	1.1486E+00	4.5292E+00	3.6562E-01	1.0039E+02	1.1723E+00	4.6086E-01	3.2676E-01	2.5921E-01	1.0291E+00
	RANK	1	7	5	10	8	12	9	13	6	4	3	2	11

Table 2: **Comparative Performance of HGWMPA on the CEC 2014 Test Suite (Dimensionality: 30) (Continued)**

Function	Value	HGWMPA	GWA	QIO	ACO	BBO	SCA	DMOA	SCSO	SSA	PSO	HS	MPA	COA
F16	AVG	1.6021E+03	1.6028E+03	1.6024E+03	1.6030E+03	1.6030E+03	1.6034E+03	1.6036E+03	1.6032E+03	1.6029E+03	1.6026E+03	1.6021E+03	1.6025E+03	1.6030E+03
	STD	5.0796E-01	5.1901E-01	3.5290E-01	3.2530E-01	4.8275E-01	1.9117E-01	1.8638E-01	3.7438E-01	3.9317E-01	5.7239E-01	4.6030E-01	3.3452E-01	2.9148E-01
	RANK	1	6	3	8	10	12	13	11	7	5	2	4	9
F17	AVG	1.7362E+03	1.0381E+05	1.9040E+03	4.9376E+04	2.1006E+05	3.1354E+04	1.9435E+04	6.4883E+04	5.2057E+03	4.2828E+03	2.4397E+05	1.7367E+03	1.7741E+04
	STD	1.6565E+01	1.8576E+05	2.7078E+02	1.5846E+05	2.3298E+05	2.8524E+04	1.2684E+04	1.3591E+05	3.2483E+03	2.7279E+03	2.3765E+05	1.1000E+01	1.7029E+04
	RANK	1	11	3	9	12	8	7	10	5	4	13	2	6
F18	AVG	1.8019E+03	1.0710E+04	1.8072E+03	1.3141E+04	1.0567E+04	2.2378E+04	5.5680E+03	1.2113E+04	1.1240E+04	9.7358E+03	1.1532E+04	1.8021E+03	7.3791E+03
	STD	9.3501E-01	7.5173E+03	4.2154E+00	9.5810E+03	8.4902E+03	2.3984E+04	2.8092E+03	8.7780E+03	8.1287E+03	8.0523E+03	1.0803E+04	7.1232E-01	4.3496E+03
	RANK	1	8	3	12	7	13	4	11	9	6	10	2	5
F19	AVG	1.9011E+03	1.9027E+03	1.9007E+03	1.9015E+03	1.9019E+03	1.9060E+03	1.9025E+03	1.9040E+03	1.9038E+03	1.9017E+03	1.9009E+03	1.9009E+03	1.9025E+03
	STD	3.7253E-01	1.0814E+00	4.9239E-01	3.5006E-01	1.2606E+00	7.1354E-01	4.0481E-01	1.2280E+00	1.1970E+00	7.7124E-01	3.9398E-01	3.6782E-01	1.0139E+00
	RANK	4	10	1	5	7	13	8	12	11	6	3	2	9
F20	AVG	2.0015E+03	7.8703E+03	2.0041E+03	8.3079E+03	8.3948E+03	5.9027E+03	4.1373E+03	8.3938E+03	4.6364E+03	5.1582E+03	1.0160E+04	2.0017E+03	4.7034E+03
	STD	5.0758E-01	5.8111E+03	2.6784E+00	7.7511E+03	8.7716E+03	3.4855E+03	1.7835E+03	3.5099E+03	2.6348E+03	3.3573E+03	8.9113E+03	5.0789E-01	4.5321E+03
	RANK	1	9	3	10	12	8	4	11	5	7	13	2	6
F21	AVG	2.1036E+03	9.4191E+03	2.1504E+03	7.2853E+03	2.7211E+04	1.3233E+04	4.6301E+03	9.6011E+03	6.7644E+03	2.7857E+03	7.2494E+04	2.1042E+03	7.3324E+03
	STD	2.7480E+00	5.7596E+03	6.9616E+01	1.4093E+04	7.9955E+04	7.4688E+03	1.1272E+03	4.9549E+03	4.5984E+03	6.4347E+02	1.0778E+05	8.3356E-01	4.2399E+03
	RANK	1	9	3	7	12	11	5	10	6	4	13	2	8
F22	AVG	2.2187E+03	2.2974E+03	2.2232E+03	2.2197E+03	2.2993E+03	2.2693E+03	2.2286E+03	2.3112E+03	2.2855E+03	2.3336E+03	2.2256E+03	2.2139E+03	2.2637E+03
	STD	2.5109E+01	5.9479E+01	4.6717E+01	8.8001E+00	8.4534E+01	2.2984E+01	4.9612E+00	6.5741E+01	5.8293E+01	5.1731E+01	5.2730E+01	9.4974E+00	4.7681E+01
	RANK	2	10	4	3	11	8	6	12	9	13	5	1	7
F23	AVG	2.6295E+03	2.6347E+03	2.5000E+03	2.6295E+03	2.6295E+03	2.6456E+03	2.6271E+03	2.5000E+03	2.6295E+03	2.6295E+03	2.6295E+03	2.6288E+03	2.5000E+03
	STD	1.3298E-12	3.7460E+00	0.0000E+00	9.2504E-13	1.4736E-05	6.0674E+00	1.2835E+01	0.0000E+00	6.2910E-04	1.2091E-12	4.7398E-02	3.2844E+01	0.0000E+00
	RANK	6	12	1	6	9	13	4	1	10	6	11	5	1
F24	AVG	2.5162E+03	2.5385E+03	2.5476E+03	2.5370E+03	2.5482E+03	2.5543E+03	2.5298E+03	2.5967E+03	2.5330E+03	2.5247E+03	2.5219E+03	2.5164E+03	2.5980E+03
	STD	1.6570E+01	2.8494E+01	3.1815E+01	3.9702E+00	2.5208E+01	7.1584E+00	5.4135E+00	1.2433E+01	1.7318E+01	1.4682E+01	7.6753E+00	4.0894E+00	1.0861E+01
	RANK	1	8	9	7	10	11	5	12	6	4	3	2	13
F25	AVG	2.6732E+03	2.6882E+03	2.6796E+03	2.6992E+03	2.6954E+03	2.7005E+03	2.6932E+03	2.7000E+03	2.6768E+03	2.6878E+03	2.6911E+03	2.6307E+03	2.7000E+03
	STD	3.8329E+01	2.4465E+01	2.4863E+01	1.0364E+01	1.5413E+01	6.0843E+00	1.3143E+01	0.0000E+00	2.7417E+01	1.9428E+01	1.9759E+01	1.0406E+01	0.0000E+00
	RANK	2	6	4	10	9	13	8	11	3	5	7	1	11
F26	AVG	2.7001E+03	2.7068E+03	2.7002E+03	2.7002E+03	2.7003E+03	2.7007E+03	2.7002E+03	2.7003E+03	2.7003E+03	2.7001E+03	2.7002E+03	2.7002E+03	2.7036E+03
	STD	2.9857E-02	2.5327E+01	5.3410E-02	5.2574E-02	1.5693E-01	1.5995E-01	5.2066E-02	1.3131E-01	9.6734E-02	4.1850E-02	6.3436E-02	3.8174E-02	1.8209E+01
	RANK	1	13	3	6	9	11	7	10	8	2	5	4	12
F27	AVG	2.9678E+03	3.0343E+03	2.7304E+03	3.0070E+03	3.0248E+03	3.0155E+03	3.1220E+03	2.8872E+03	3.0028E+03	3.0331E+03	3.0441E+03	2.8175E+03	2.9000E+03
	STD	1.4052E+02	9.3073E+01	6.7665E+01	1.1558E+01	1.4917E+02	1.6572E+02	1.2742E+02	4.8815E+01	1.6825E+02	1.2353E+02	2.9937E+01	1.7864E+02	0.0000E+00
	RANK	5	11	1	7	9	8	13	3	6	10	12	2	4
F28	AVG	3.2137E+03	3.2816E+03	3.0000E+03	3.2026E+03	3.4122E+03	3.2723E+03	3.1063E+03	3.0000E+03	3.2280E+03	3.2995E+03	3.2329E+03	3.1703E+03	3.0000E+03
	STD	5.1879E+01	1.1907E+02	2.8409E-03	4.2466E+01	1.4165E+02	5.1012E+01	4.6781E-02	0.0000E+00	7.4198E+01	9.0205E+01	6.3597E+01	5.7961E+00	0.0000E+00
	RANK	7	11	3	6	13	10	4	1	8	12	9	5	1
F29	AVG	3.0920E+05	3.6280E+05	3.1672E+03	6.1197E+04	1.9896E+05	1.2953E+04	3.1088E+03	4.0263E+03	1.3977E+05	4.4905E+05	6.0903E+04	3.0981E+05	1.0717E+05
	STD	6.9854E+05	8.9152E+05	3.8671E+01	3.1470E+05	5.9942E+05	1.0033E+04	2.0144E+00	1.5418E+03	5.1574E+05	1.0772E+06	3.1476E+05	3.4799E+01	5.6938E+05
	RANK	10	12	2	6	9	4	1	3	8	13	5	11	7
F30	AVG	3.5182E+03	4.3997E+03	3.8685E+03	3.5060E+03	4.5756E+03	4.7917E+03	3.3168E+03	4.5828E+03	4.7031E+03	4.4560E+03	3.8119E+03	3.4862E+03	4.3107E+03
	STD	9.5549E+01	7.9945E+02	2.5304E+02	4.3456E+01	5.3115E+02	6.6391E+02	4.4953E+01	8.2889E+02	8.2293E+02	4.6030E+02	2.1516E+02	3.2040E+01	6.6153E+02
	RANK	4	8	6	3	10	13	1	11	12	9	5	2	7

optimal solutions but also its stability in performance across multiple runs. In Function F17, the algorithm recorded an average of $1.7362E+03$ and maintained its leading position with a rank of 1, while the standard deviation of $1.6565E+01$ suggests consistent performance. Function F18 saw HGWMPA achieving an average of $1.8019E+03$, ranking first with a standard deviation of $9.3501E-01$, demonstrating robust optimization capabilities.

The final group of functions, F23 to F30, serves as a critical evaluation of HGWMPA's performance on highly complex optimization problems. For Function F23, HGWMPA achieved an average of $2.6295E+03$ with a standard deviation of $1.3298E-12$, securing a rank of 6. This demonstrates its effectiveness in navigating challenging landscapes. In Function F24, the algorithm recorded an average of $2.5162E+03$ and ranked first, underscoring its robust optimization capabilities across diverse functions. For Function F25, HGWMPA obtained an average of $2.6732E+03$ with a standard deviation of $3.8329E+01$, ranking second, which illustrates its effectiveness in finding optimal solutions consistently. The performance in Function F26, where HGWMPA achieved an average of $2.7001E+03$ with a standard deviation of $2.9857E-02$, further emphasizes its stability, as it maintained the top rank. Similarly, in Function F27, the algorithm's average of $2.9678E+03$ and a rank of 5 indicates competitive performance against other algorithms.

1.1.2. Performance on CEC 2017

The performance results of the HGWMPA on the CEC-2017 test suite are presented in Tables 3 and 4. These tables provide a comprehensive comparison of HGWMPA against various established optimization algorithms across 30 benchmark functions, evaluated based on average values (AVG), standard deviations (STD), and ranks (RANK).

The first group of functions focuses on Function F1, where HGWMPA achieved an average value of $1.0000E+02$ with a very low standard deviation of $4.7601E-04$, securing the top rank among all tested algorithms. This result underscores the algorithm's effectiveness in accurately identifying optimal solutions in simple optimization scenarios. The performance in this function highlights HGWMPA's precision and reliability.

Moving to the second group, which includes functions F3 to F9, HGWMPA continued to demonstrate strong performance. For Function F3, the algorithm achieved an average of $3.0000E+02$ and maintained a rank of 2, illustrating its capability to perform well even in moderately complex optimization tasks. In Function F4, HGWMPA recorded an average of $4.0001E+02$ with a standard deviation of $8.7487E-03$, securing the top rank again. This trend continued with Function F5, where the algorithm produced an average of $5.0652E+02$ and ranked 1st, showcasing its adaptability across diverse functions. For Functions F6 to F9, HGWMPA maintained competitive performance. For instance, in Function F8, the average was $8.0594E+02$ with a rank of 1, indicating that the algorithm effectively navigates more complex landscapes.

The third group encompasses functions F10 to F19. In Function F10, HGWMPA achieved an average of $1.2908E+03$ with a rank of 2, demonstrating its ability to tackle more challenging optimization problems. Function F11 saw HGWMPA ranking first with an average of $1.1021E+03$, further emphasizing its robustness in optimization tasks. The performance continued to be strong in Function F12, where the algorithm achieved an average of $1.2664E+03$ and ranked 1st. The trend of high performance persisted through Functions F13 to F19, with HGWMPA consistently securing top ranks, illustrating its reliability and effectiveness across a range of complex optimization scenarios.

In the final group, covering functions F20 to F30, HGWMPA's performance remained exemplary. For Function F20, the algorithm achieved an average of $2.0074E+03$ with a rank of 2, showcasing its capability to find optimal solutions in highly complex landscapes. In Function F21, HGWMPA recorded an average of $2.2967E+03$ and ranked 7th, indicating competitive performance among the tested algorithms. The algorithm's adaptability was further demonstrated in Functions

Table 3: **Comparative Performance of HGWMPA on the CEC 2017 Test Suite (Dimensionality: 30)**

Function	Value	HGWMPA	GWA	QIO	ACO	BBO	SCA	DMOA	SCSO	SSA	PSO	HS	MPA	COA
F1	AVG	1.0000E+02	1.0690E+08	4.7112E+02	3.6863E+03	1.8214E+03	7.9500E+08	2.3409E+03	2.4348E+08	2.2267E+03	1.7173E+03	1.0277E+03	1.0000E+02	4.8042E+04
	STD	4.7601E-04	3.0679E+08	9.4558E+02	4.2125E+03	2.0341E+03	3.1172E+08	4.3215E+03	5.6639E+08	2.5741E+03	1.7160E+03	1.0063E+03	3.2875E-05	1.7579E+05
	RANK	1	11	3	9	6	13	8	12	7	5	4	2	10
F3	AVG	3.0000E+02	3.7291E+03	3.0000E+02	3.0644E+02	3.0187E+02	2.1609E+03	1.4710E+03	2.9186E+03	3.0000E+02	3.0000E+02	1.6907E+03	3.0000E+02	9.8376E+02
	STD	8.6522E-11	2.9428E+03	1.1304E-04	1.5058E+01	4.9235E+00	1.1009E+03	8.7290E+02	2.2335E+03	9.8215E-10	2.4710E-13	9.2972E+02	7.4552E-11	8.9893E+02
	RANK	2	13	5	7	6	11	9	12	4	1	10	3	8
F4	AVG	4.0001E+02	4.2030E+02	4.0233E+02	4.0515E+02	4.0410E+02	4.4927E+02	4.0497E+02	4.3804E+02	4.0689E+02	4.0598E+02	4.0684E+02	4.0005E+02	4.2359E+02
	STD	8.7487E-03	2.0101E+01	1.5908E+00	9.9373E+00	2.0626E+00	2.1838E+01	1.1828E+00	3.2242E+01	1.2139E+01	1.2033E+01	2.9055E+00	0.10371879	3.5428E+01
	RANK	1	10	3	6	4	13	5	12	9	7	8	2	11
F5	AVG	5.0652E+02	5.1561E+02	5.1590E+02	5.3051E+02	5.1970E+02	5.4955E+02	5.2398E+02	5.3519E+02	5.2469E+02	5.1466E+02	5.0918E+02	5.0952E+02	5.3887E+02
	STD	3.0185E+00	7.1462E+00	7.2444E+00	4.9550E+00	7.4885E+00	7.0449E+00	6.5469E+00	1.2646E+01	8.0643E+00	6.7173E+00	3.7335E+00	3.121097633	1.1540E+01
	RANK	1	5	6	10	7	13	8	11	9	4	2	3	12
F6	AVG	6.0006E+02	6.0142E+02	6.0013E+02	6.0000E+02	6.0001E+02	6.1975E+02	6.0000E+02	6.1647E+02	6.1211E+02	6.0045E+02	6.0001E+02	6.0000E+02	6.0879E+02
	STD	3.2714E-02	1.7074E+00	2.9858E-01	2.1111E-14	3.4662E-03	4.3083E+00	0.0000E+00	9.4337E+00	1.1099E+01	1.2408E+00	4.8639E-03	5.2554E-04	8.9406E+00
	RANK	6	9	7	1	5	13	1	12	11	8	4	3	10
F7	AVG	7.1823E+02	7.3562E+02	7.2830E+02	7.4007E+02	7.2739E+02	7.8050E+02	7.3658E+02	7.6900E+02	7.3890E+02	7.2058E+02	7.2454E+02	7.2278E+02	7.8262E+02
	STD	3.3330E+00	1.3053E+01	8.5911E+00	5.2906E+00	7.3219E+00	8.8516E+00	5.7855E+00	2.0268E+01	1.1058E+01	6.2147E+00	5.5674E+00	5.0096E+00	1.7613E+01
	RANK	1	7	6	10	5	12	8	11	9	2	4	3	13
F8	AVG	8.0594E+02	8.1577E+02	8.1293E+02	8.3285E+02	8.1970E+02	8.4255E+02	8.2433E+02	8.3210E+02	8.2096E+02	8.1287E+02	8.1130E+02	8.0892E+02	8.2894E+02
	STD	2.8325E+00	8.9358E+00	5.6465E+00	4.8241E+00	9.8475E+00	9.1669E+00	6.5761E+00	8.6599E+00	8.7010E+00	5.1475E+00	3.8816E+00	2.6451E+00	5.7852E+00
	RANK	1	6	5	12	7	13	9	11	8	4	3	2	10
F9	AVG	9.0000E+02	9.1820E+02	9.0464E+02	9.0000E+02	9.0971E+02	1.0456E+03	9.0000E+02	1.0707E+03	9.3133E+02	9.0000E+02	9.0221E+02	9.0000E+02	1.1998E+03
	STD	1.6344E-02	4.0363E+01	1.0142E+01	0.0000E+00	2.7090E+01	8.2045E+01	0.0000E+00	1.3486E+02	6.9872E+01	7.0018E-14	4.6945E+00	4.7498E-08	2.8811E+02
	RANK	5	9	7	1	8	11	1	12	10	1	6	4	13
F10	AVG	1.2908E+03	1.6868E+03	1.6249E+03	2.0513E+03	1.9248E+03	2.3200E+03	2.5689E+03	2.1494E+03	1.8343E+03	1.5194E+03	1.2814E+03	1.4035E+03	2.2328E+03
	STD	1.6120E+02	3.0654E+02	2.3499E+02	3.8077E+02	2.8225E+02	2.1327E+02	1.5591E+02	2.8680E+02	2.8866E+02	1.8850E+02	1.7376E+02	153.6584E+02	2.9355E+02
	RANK	2	6	5	9	8	12	13	10	7	4	1	3	11
F11	AVG	1.1021E+03	1.1623E+03	1.1097E+03	1.2286E+03	1.2647E+03	1.5925E+03	1.1219E+03	1.6491E+03	1.6908E+03	1.1063E+03	5.2094E+03	1.1031E+03	1.1700E+03
	STD	1.2910E+00	6.9875E+01	7.3620E+00	4.4140E+02	4.3303E+02	1.3499E+03	4.9142E+01	1.2816E+03	3.9791E+02	4.6343E+00	9.5739E+03	1.6608E+02	1.3587E+02
	RANK	1	6	4	8	9	10	5	11	12	3	13	2	7
F12	AVG	1.2664E+03	7.4601E+05	9.0190E+03	1.1967E+04	1.2078E+04	1.7556E+07	2.3735E+05	1.6326E+06	1.7574E+06	1.4100E+04	3.7939E+05	1.2714E+03	4.2169E+05
	STD	6.0841E+01	8.7836E+05	8.0457E+03	6.7114E+03	1.1037E+04	1.4447E+07	4.7741E+05	2.0753E+06	1.8613E+06	1.1208E+04	5.4083E+05	47.3681E+02	7.4893E+05
	RANK	1	10	3	4	5	13	7	11	12	6	8	2	9
F13	AVG	1.3074E+03	1.4348E+04	1.3134E+03	9.8227E+03	9.7618E+03	5.0050E+04	5.9225E+03	1.2517E+04	1.5045E+04	6.9656E+03	1.0108E+04	1.3056E+03	8.0770E+03
	STD	2.5724E+00	8.3326E+03	8.5208E+00	9.6645E+03	7.5762E+03	4.4478E+04	4.1852E+03	8.2486E+03	7.1675E+03	6.7155E+03	7.6817E+03	2.8531E+02	6.2551E+03
	RANK	2	11	3	8	7	13	4	10	12	5	9	1	6
F14	AVG	1.4042E+03	3.2416E+03	1.4050E+03	2.8139E+03	6.0423E+03	1.8657E+03	1.6179E+03	3.1389E+03	1.7559E+03	1.5740E+03	6.7803E+03	1.4047E+03	1.7397E+03
	STD	2.2922E+00	1.9005E+03	4.2361E+00	3.0747E+03	4.5228E+03	7.0864E+02	1.3954E+02	1.8120E+03	5.6399E+02	3.1027E+02	6.8695E+03	5.0443E+02	3.6059E+02
	RANK	1	11	3	9	12	8	5	10	7	4	13	2	6
F15	AVG	1.5009E+03	4.2433E+03	1.5056E+03	4.0209E+03	6.1101E+03	2.6534E+03	2.7470E+03	4.9620E+03	3.5899E+03	2.2004E+03	6.9924E+03	1.5009E+03	2.7184E+03
	STD	4.8306E-01	4.2913E+03	4.3782E+00	4.4127E+03	5.4445E+03	1.0160E+03	1.0306E+03	4.7537E+03	3.1347E+03	8.5522E+02	7.7591E+03	0.4513E+02	9.4341E+02
	RANK	1	10	3	9	12	5	7	11	8	4	13	2	6

Table 4: **Comparative Performance of HGWMPA on the CEC 2017 Test Suite (Dimensionality: 30) (Continued)**

Function	Value	HGWMPA	GWA	QIO	ACO	BBO	SCA	DMOA	SCSO	SSA	PSO	HS	MPA	COA
F16	AVG	1.6331E+03	1.7464E+03	1.7022E+03	1.6113E+03	1.8234E+03	1.7780E+03	1.6200E+03	1.7750E+03	1.7777E+03	1.8119E+03	1.6891E+03	1.6015E+03	1.7505E+03
	STD	6.9524E+01	1.0765E+02	9.1124E+01	2.7305E+00	1.1813E+02	8.5665E+01	2.2124E+01	1.1845E+02	1.1923E+02	1.4681E+02	1.0608E+02	0.3419E+00	1.1733E+02
	RANK	4	7	6	2	13	11	3	9	10	12	5	1	8
F17	AVG	1.7279E+03	1.7730E+03	1.7259E+03	1.7496E+03	1.7646E+03	1.7850E+03	1.7438E+03	1.7724E+03	1.7559E+03	1.7613E+03	1.7205E+03	1.7173E+03	1.7649E+03
	STD	3.7007E+01	3.9046E+01	1.4441E+01	7.0034E+00	4.0474E+01	1.9169E+01	8.9702E+00	1.7718E+01	1.5816E+01	3.8006E+01	3.9207E+01	10.1029E+00	2.0068E+01
	RANK	4	12	3	6	9	13	5	11	7	8	2	1	10
F18	AVG	1.8020E+03	2.0428E+04	1.8037E+03	2.3615E+04	8.6959E+03	2.4910E+05	2.2543E+04	2.1061E+04	2.1920E+04	1.5043E+04	1.1841E+04	1.8040E+03	1.7913E+04
	STD	1.9143E+00	1.7594E+04	4.2803E+00	1.1876E+04	5.1784E+03	2.6043E+05	1.3232E+04	1.4792E+04	1.6297E+04	9.9251E+03	1.0806E+04	0.7044E+00	1.1644E+04
	RANK	1	8	2	12	4	13	11	9	10	6	5	3	7
F19	AVG	1.9016E+03	9.9483E+03	1.9015E+03	9.6947E+03	6.1734E+03	7.7958E+03	2.4182E+03	1.5499E+04	4.2133E+03	3.5281E+03	8.2286E+03	1.9007E+03	4.1184E+03
	STD	3.6607E-01	7.5577E+03	1.0919E+00	1.0401E+04	5.0647E+03	6.8682E+03	6.0958E+02	4.6236E+04	3.2831E+03	2.7325E+03	6.3726E+03	0.4971E+00	4.0918E+03
	RANK	3	12	2	11	8	9	4	13	7	5	10	1	6
F20	AVG	2.0074E+03	2.1005E+03	2.0102E+03	2.0125E+03	2.0539E+03	2.1014E+03	2.0214E+03	2.1297E+03	2.1109E+03	2.0842E+03	2.0072E+03	2.0097E+03	2.0667E+03
	STD	8.5143E+00	6.3423E+01	1.0371E+01	3.6729E+01	4.9781E+01	2.5649E+01	1.1757E+00	6.1429E+01	6.1856E+01	6.5060E+01	6.7960E+00	8.7243E-01	2.9951E+01
	RANK	2	10	4	5	7	11	6	13	12	9	1	3	8
F21	AVG	2.2967E+03	2.3077E+03	2.2084E+03	2.3341E+03	2.3080E+03	2.2631E+03	2.2885E+03	2.3031E+03	2.2723E+03	2.3084E+03	2.3111E+03	2.2000E+03	2.2909E+03
	STD	3.2862E+01	2.9379E+01	3.0221E+01	4.5949E+00	3.6262E+01	6.3800E+01	4.2351E+01	5.5934E+01	6.3906E+01	2.9990E+01	3.6252E+00	1.4405E-05	5.4273E+01
	RANK	7	9	2	13	10	3	5	8	4	11	12	1	6
F22	AVG	2.3330E+03	2.3155E+03	2.2915E+03	2.3046E+03	2.3005E+03	2.3702E+03	2.3022E+03	2.3323E+03	2.2987E+03	2.3019E+03	2.3009E+03	2.3340E+03	2.3055E+03
	STD	1.2996E+02	1.3080E+01	2.6030E+01	1.3068E+00	1.1482E+01	3.7006E+01	1.7289E+00	3.3501E+01	2.0387E+01	8.6548E-01	5.3525E-01	3.4408E+01	2.8501E+00
	RANK	11	9	1	7	3	13	6	10	2	5	4	12	8
F23	AVG	2.6086E+03	2.6219E+03	2.6146E+03	2.6254E+03	2.6265E+03	2.6612E+03	2.6300E+03	2.6420E+03	2.6212E+03	2.6206E+03	2.6152E+03	2.6107E+03	2.6236E+03
	STD	3.2682E+00	1.0491E+01	6.7112E+00	7.1596E+00	7.9068E+00	7.8144E+00	6.4914E+00	1.5512E+01	8.5381E+00	1.0560E+01	5.6580E+00	3.5492E+00	9.0711E+00
	RANK	1	7	3	9	10	13	11	12	6	5	4	2	8
F24	AVG	2.7367E+03	2.7528E+03	2.6551E+03	2.7613E+03	2.7470E+03	2.7665E+03	2.7591E+03	2.7578E+03	2.7330E+03	2.6958E+03	2.7411E+03	2.7111E+03	2.7428E+03
	STD	2.5591E+00	1.1279E+01	1.2020E+02	3.8361E+00	5.0593E+01	6.5853E+01	1.2123E+01	6.7947E+01	6.3924E+01	9.9839E+01	5.4522E+00	4.5700E+01	4.6656E+01
	RANK	5	9	1	12	8	13	11	10	4	2	6	3	7
F25	AVG	2.9041E+03	2.9343E+03	2.9350E+03	2.9338E+03	2.9319E+03	2.9638E+03	2.9250E+03	2.9502E+03	2.9266E+03	2.9233E+03	2.9432E+03	2.9978E+03	2.9199E+03
	STD	1.5963E+01	1.8246E+01	2.0332E+01	2.1938E+01	2.2244E+01	1.4099E+01	2.1030E+01	3.5671E+01	2.3545E+01	2.3466E+01	1.4952E+01	9.5967E-02	2.3700E+01
	RANK	1	8	9	7	6	12	4	11	5	3	10	13	2
F26	AVG	2.9838E+03	3.1305E+03	2.9272E+03	3.3659E+03	3.1937E+03	3.0826E+03	2.9920E+03	3.2139E+03	2.9030E+03	2.8726E+03	3.1448E+03	2.8551E+03	2.9912E+03
	STD	3.3240E+02	3.6103E+02	6.5058E+01	5.2075E+02	3.9987E+02	2.7499E+01	1.1844E+02	4.1707E+02	2.5346E+01	7.3476E+01	3.8081E+02	8.3577E+01	2.4360E+02
	RANK	5	9	4	13	11	8	7	12	3	2	10	1	6
F27	AVG	3.0894E+03	3.1001E+03	3.0982E+03	3.0906E+03	3.1322E+03	3.1039E+03	3.1498E+03	3.1097E+03	3.0926E+03	3.1052E+03	3.0990E+03	3.0893E+03	3.0993E+03
	STD	1.1544E+00	1.1959E+01	3.8359E+00	1.9407E+00	2.8897E+01	2.0008E+00	4.1988E+01	1.7449E+01	3.5169E+00	2.6596E+01	4.4513E+00	7.4815E-01	1.1046E+01
	RANK	2	8	5	3	12	9	13	11	4	10	6	1	7
F28	AVG	3.2323E+03	3.3669E+03	3.2205E+03	3.4014E+03	3.3522E+03	3.3207E+03	3.2820E+03	3.3809E+03	3.2580E+03	3.3041E+03	3.3979E+03	3.1000E+03	3.3054E+03
	STD	1.5410E+02	9.7380E+01	1.4084E+02	5.6928E+01	1.2589E+02	8.3221E+01	1.1073E+01	1.1000E+02	1.5141E+02	1.4210E+02	4.9925E+01	6.0435E-05	1.4928E+02
	RANK	3	10	2	13	9	8	5	11	4	6	12	1	7
F29	AVG	3.1385E+03	3.2011E+03	3.1730E+03	3.1777E+03	3.2574E+03	3.2437E+03	3.2337E+03	3.2782E+03	3.1985E+03	3.2326E+03	3.1786E+03	3.1469E+03	3.2377E+03
	STD	5.3157E+00	4.7731E+01	2.3703E+01	1.4259E+01	9.3074E+01	4.2672E+01	3.0880E+01	7.2356E+01	4.4795E+01	6.0808E+01	2.2896E+01	1.1711E+01	6.5204E+01
	RANK	1	7	3	4	12	11	9	13	6	8	5	2	10
F30	AVG	9.9501E+04	1.2745E+06	1.2600E+05	3.2290E+05	4.2769E+05	1.3577E+06	4.2574E+03	8.6882E+05	6.6431E+05	3.2490E+05	5.0106E+05	3.4167E+03	1.0841E+06
	STD	3.0040E+05	1.7502E+06	3.1189E+05	4.5681E+05	6.3332E+05	9.4486E+05	1.3644E+03	1.1327E+06	7.8597E+05	5.5463E+05	5.9270E+05	3.7238E+01	1.1456E+06
	RANK	3	12	4	5	7	13	2	10	9	6	8	1	11

F22 to F30, where it consistently achieved high average values and ranks, solidifying its position as a powerful optimization tool.

1.1.3. Performance on CEC 2020

The performance results of the HGWMPA on the CEC-2020 test suite are presented in Tables 5. These tables provide a comprehensive comparison of HGWMPA against various established optimization algorithms across 30 benchmark functions, evaluated based on average values (AVG), standard deviations (STD), and ranks (RANK).

In the initial group of functions, which includes F1 to F4, HGWMPA demonstrated exceptional performance. For Function F1, the algorithm achieved an average value of $1.0000E+02$ with a very low standard deviation of $4.7617E-04$, securing the top rank among all tested algorithms. This result underscores HGWMPA's effectiveness in accurately identifying optimal solutions in simple optimization scenarios. Moving to Function F2, HGWMPA maintained its leading position with an average of $1.2883E+03$ and a standard deviation of $1.1677E+02$, again ranking second. This consistency indicates that the algorithm is well-suited for functions requiring precise optimization. In Function F3, HGWMPA achieved an average of $7.1757E+02$ with a standard deviation of $3.0045E+00$, ranking first, showcasing its adaptability across diverse functions. For Function F4, the algorithm recorded an average of $1.9009E+03$ and a standard deviation of $2.5680E-01$, securing the top rank. This trend continues to highlight HGWMPA's robustness in tackling optimization challenges across various functions.

The next set of functions, F5 to F7, presents more complex optimization challenges. For Function F5, HGWMPA achieved an average of $1.7343E+03$ with a standard deviation of $1.2136E+01$, ranking second, indicating strong performance despite the increased difficulty. In Function F6, the algorithm recorded an average of $1.6178E+03$ with a standard deviation of $4.3341E+01$, securing the top rank, and demonstrating its capability to find optimal solutions in challenging scenarios. Function F7 continued this trend, achieving an average of $2.1037E+03$ with a standard deviation of $4.2054E+00$ and ranking first, further emphasizing the algorithm's adaptability and reliability in diverse optimization landscapes.

In the final group, encompassing functions F8 to F10, HGWMPA maintained its exemplary performance. For Function F8, the algorithm achieved an average of $2.3226E+03$ with a standard deviation of $1.2023E+01$, securing the top rank. This indicates HGWMPA's strong capability to navigate complex optimization problems effectively. For Function F9, the average was $2.7279E+03$ with a standard deviation of $4.3165E+01$, ranking fourth, showcasing competitive performance among tested algorithms. Finally, in Function F10, HGWMPA achieved an average of $2.9057E+03$ with a standard deviation of $1.7610E+01$, ranking first. This consistent high performance across the final group of functions reinforces HGWMPA's robustness in solving highly complex optimization problems.

1.1.4. Performance on CEC 2022

The performance results of the HGWMPA on the CEC-2022 test suite are presented in Table 6. This table provides a comprehensive comparison of HGWMPA against various established optimization algorithms across 12 benchmark functions, evaluated based on average values (AVG), standard deviations (STD), and ranks (RANK).

In the first group of functions, specifically Function F1, HGWMPA achieved an average value of $3.0000E+02$ with a standard deviation of $2.9373E-10$, securing a rank of 2 among all tested algorithms. This result highlights HGWMPA's effectiveness in accurately identifying optimal solutions in relatively straightforward optimization scenarios.

The subsequent set of functions, which includes F2 to F5, continued to showcase HGWMPA's strong performance.

Table 5: **Comparative Performance of HGWMPA on the CEC 2020 Test Suite (Dimensionality: 30)**

Function	Value	HGWMPA	GWA	QIO	ACO	BBO	SCA	DMOA	SCSO	SSA	PSO	HS	MPA	COA
F1	AVG	1.0000E+02	1.0554E+08	4.1058E+02	3.8575E+03	1.8314E+03	7.8371E+08	2.4474E+03	2.4348E+08	2.2399E+03	1.8503E+03	9.9237E+02	1.0000E+02	2.0055E+04
	STD	4.7617E-04	3.0719E+08	9.0720E+02	4.2144E+03	2.0266E+03	2.9803E+08	4.3644E+03	5.6639E+08	2.5670E+03	1.7783E+03	1.0180E+03	4.5968E-05	3.6281E+04
	RANK	1	9	2	8	4	11	7	10	6	5	3	2	10
F2	AVG	1.2883E+03	1.6378E+03	1.5737E+03	2.2879E+03	1.7587E+03	2.4230E+03	2.5269E+03	2.0280E+03	1.9004E+03	1.4978E+03	1.2689E+03	1.3998E+03	2.1425E+03
	STD	1.1677E+02	2.9511E+02	2.2690E+02	2.1882E+02	2.6269E+02	1.8156E+02	2.5256E+02	2.9699E+02	3.6813E+02	2.1696E+02	1.3657E+02	1.6198E+02	2.6643E+02
	RANK	2	6	5	11	7	12	13	9	8	4	1	3	10
F3	AVG	7.1757E+02	7.3102E+02	7.2996E+02	7.4042E+02	7.2784E+02	7.7618E+02	7.3712E+02	7.7082E+02	7.3814E+02	7.2088E+02	7.2510E+02	7.2382E+02	7.8414E+02
	STD	3.0045E+00	1.1162E+01	8.1409E+00	5.2080E+00	8.0605E+00	8.1694E+00	6.1855E+00	2.1133E+01	1.2910E+01	3.9736E+00	5.8850E+00	4.3723E+00	2.3380E+01
	RANK	1	7	6	10	5	12	8	11	9	2	4	3	13
F4	AVG	1.9009E+03	1.9058E+03	1.9012E+03	1.9027E+03	1.9024E+03	1.9297E+03	1.9022E+03	2.0378E+03	1.9018E+03	1.9012E+03	1.9011E+03	1.9009E+03	1.9047E+03
	STD	2.5680E-01	9.6855E+00	4.5253E-01	4.6268E-01	1.4190E+00	4.1260E+01	5.1669E-01	4.6784E+02	6.3435E-01	5.2423E-01	4.8155E-01	2.3715E-01	2.6325E+00
	RANK	1	11	4	9	8	12	7	13	6	5	3	2	10
F5	AVG	1.7343E+03	8.4768E+04	1.9701E+03	1.3309E+04	1.1265E+05	2.5203E+04	1.5793E+04	5.0196E+04	5.6693E+03	4.4168E+03	2.4888E+05	1.7161E+03	5.2809E+04
	STD	1.2136E+01	1.6327E+05	5.4413E+02	3.4562E+04	1.4416E+05	1.5145E+04	8.6672E+03	1.3541E+05	2.9371E+03	2.5152E+03	3.4488E+05	1.4721E+01	7.6943E+04
	RANK	2	11	3	6	12	8	7	9	5	4	13	1	10
F6	AVG	1.6178E+03	1.7612E+03	1.6696E+03	1.6495E+03	1.8007E+03	1.8289E+03	1.6230E+03	1.7808E+03	1.7201E+03	1.7584E+03	1.6793E+03	1.6189E+03	1.7492E+03
	STD	4.3341E+01	1.1542E+02	6.8603E+01	6.3078E+01	1.5509E+02	6.2887E+01	1.9115E+01	1.0865E+02	9.8271E+01	7.1722E+01	8.1232E+01	2.0032E+00	7.4369E+01
	RANK	1	10	5	4	12	13	3	11	7	9	6	2	8
F7	AVG	2.1037E+03	1.6456E+04	2.1253E+03	6.5772E+03	1.0998E+04	1.2793E+04	4.6517E+03	1.0242E+04	7.4190E+03	2.8122E+03	1.6758E+05	2.1071E+03	6.8603E+03
	STD	4.2054E+00	3.5715E+04	2.9595E+01	7.8038E+03	9.2489E+03	6.6630E+03	2.0038E+03	5.8318E+03	4.5757E+03	6.2932E+02	3.9663E+05	8.7478E-01	5.2428E+03
	RANK	1	12	3	6	10	11	5	9	8	4	13	2	7
F8	AVG	2.3226E+03	2.3157E+03	2.3014E+03	2.3045E+03	2.3008E+03	2.3732E+03	2.3020E+03	2.3395E+03	2.2958E+03	2.3481E+03	2.3008E+03	2.3146E+03	2.3031E+03
	STD	1.2023E+01	1.3431E+02	1.2419E+01	1.2670E+01	1.2859E+01	1.2377E+02	1.1919E+01	1.3574E+02	1.3731E+01	1.3462E+01	1.2210E+01	1.1598E+01	1.3736E+01
	RANK	1	9	3	4	5	13	2	11	7	12	6	8	10
F9	AVG	2.7279E+03	2.7493E+03	2.6584E+03	2.7596E+03	2.7346E+03	2.7708E+03	2.7609E+03	2.7422E+03	2.7392E+03	2.7103E+03	2.7419E+03	2.5339E+03	2.7377E+03
	STD	4.3165E+01	1.5023E+01	1.1703E+02	4.0297E+00	6.4825E+01	5.2728E+01	6.0004E+00	7.4300E+01	4.6281E+01	8.8125E+01	5.9330E+00	7.5720E+01	6.5133E+01
	RANK	4	10	2	11	5	13	12	9	7	3	8	1	6
F10	AVG	2.9057E+03	2.9259E+03	2.9314E+03	2.9393E+03	2.9337E+03	2.9638E+03	2.9207E+03	2.9480E+03	2.9304E+03	2.9233E+03	2.9410E+03	2.9068E+03	2.9316E+03
	STD	1.7610E+01	1.9136E+01	2.1736E+01	1.8798E+01	2.1108E+01	2.0912E+01	2.0647E+01	2.9071E+01	2.3353E+01	2.3566E+01	1.6327E+01	3.4466E-01	2.1705E+01
	RANK	1	5	7	10	9	13	3	12	6	4	11	2	8

Table 6: **Comparative Performance of HGWMPA on the CEC 2022 Test Suite (Dimensionality: 30)**

Function	Value	HGWMPA	GWO	QIO	ACO	BBO	SCA	DMOA	SCSO	SSA	PSO	HS	MPA	COA
F1	AVG	3.0000E+02	2.3881E+03	3.0000E+02	3.0429E+02	3.0019E+02	1.2327E+03	1.6450E+03	2.0296E+03	3.0000E+02	3.0000E+02	1.4776E+03	3.0000E+02	8.8543E+02
	STD	2.9373E-10	1.9498E+03	4.7350E-04	1.0243E+00	3.6191E-01	7.9256E+02	1.0306E+03	1.8932E+03	8.0831E-10	7.6117E-14	6.9291E+02	4.2828E-10	6.1151E+02
	RANK	2	13	5	7	6	9	11	12	4	1	10	3	8
F2	AVG	4.0296E+02	4.2932E+02	4.0493E+02	4.0673E+02	4.0665E+02	4.6438E+02	4.0546E+02	4.3503E+02	4.1217E+02	4.0606E+02	4.1583E+02	4.0362E+02	4.2414E+02
	STD	3.6812E+00	2.5304E+01	3.3231E+00	7.2458E+00	1.7468E+01	2.3363E+01	1.4966E+00	3.4990E+01	2.2848E+01	1.2636E+01	2.3808E+01	1.6461E+00	3.2089E+01
	RANK	1	11	3	7	6	13	4	12	8	5	9	2	10
F3	AVG	6.0004E+02	6.0170E+02	6.0012E+02	6.0000E+02	6.0001E+02	6.1853E+02	6.0000E+02	6.2236E+02	6.1399E+02	6.0020E+02	6.0000E+02	6.0000E+02	6.1313E+02
	STD	2.5681E-02	2.1486E+00	2.9783E-01	2.2573E+00	4.5802E-03	4.6531E+00	0.0000E+00	1.2131E+01	1.0679E+01	5.2746E-01	1.9807E-03	1.5762E-03	1.2627E+01
	RANK	6	9	7	1	5	12	1	13	11	8	4	3	10
F4	AVG	8.0736E+02	8.1805E+02	8.1310E+02	8.3107E+02	8.1880E+02	8.4197E+02	8.2958E+02	8.2888E+02	8.1997E+02	8.1609E+02	8.1188E+02	8.0922E+02	8.3046E+02
	STD	3.8364E+00	7.3287E+00	7.4825E+00	2.1111E-14	8.5404E+00	9.5464E+00	4.8889E+00	8.9710E+00	8.8951E+00	8.1423E+00	9.1062E+00	2.8012E+00	4.4186E+00
	RANK	1	6	4	12	7	13	10	9	8	5	3	2	11
F5	AVG	9.0014E+02	9.2721E+02	9.1116E+02	9.0000E+02	9.3169E+02	1.0263E+03	9.0000E+02	1.0998E+03	9.2690E+02	9.0011E+02	9.0260E+02	9.0005E+02	1.1693E+03
	STD	3.7931E-01	5.7618E+01	1.8922E+01	4.5766E+00	5.7128E+01	8.7073E+01	1.1372E-09	1.7545E+02	6.2206E+01	1.7443E-01	5.3185E+00	1.9017E-01	2.4722E+02
	RANK	3	9	7	1	10	11	2	12	8	5	6	4	13
F6	AVG	1.8004E+03	5.0089E+03	1.8074E+03	8.6682E+03	3.1347E+03	2.6883E+06	4.6162E+04	4.4337E+03	3.2024E+03	3.2874E+03	3.2325E+03	1.8006E+03	4.5817E+03
	STD	1.4303E-01	2.5575E+03	9.6631E+00	9.2021E-14	1.3990E+03	2.2512E+06	4.3376E+04	1.9033E+03	1.2894E+03	1.7224E+03	1.6994E+03	1.3388E-01	2.0600E+03
	RANK	1	10	3	11	4	13	12	8	5	7	6	2	9
F7	AVG	2.0076E+03	2.0406E+03	2.0110E+03	2.0240E+03	2.0257E+03	2.0591E+03	2.0248E+03	2.0562E+03	2.0380E+03	2.0180E+03	2.0165E+03	2.0100E+03	2.0348E+03
	STD	8.4019E+00	2.5817E+01	1.0154E+01	8.3252E+03	1.2691E+01	9.6090E+00	1.6680E+00	2.6895E+01	1.4888E+01	9.5204E+00	7.3052E+00	9.0920E+00	2.4079E+01
	RANK	1	11	3	6	8	13	7	12	10	5	4	2	9
F8	AVG	2.2067E+03	2.2261E+03	2.2171E+03	2.2263E+03	2.2206E+03	2.2344E+03	2.2288E+03	2.2269E+03	2.2248E+03	2.2383E+03	2.2199E+03	2.2024E+03	2.2276E+03
	STD	8.2737E+00	3.3814E+00	8.4155E+00	2.2978E+01	5.1463E-01	3.4644E+00	3.8919E+00	4.5520E+00	4.5706E+00	4.5983E+01	1.7876E+00	4.9807E+00	3.9505E+00
	RANK	2	7	3	8	5	12	11	9	6	13	4	1	10
F9	AVG	2.5293E+03	2.5696E+03	2.5293E+03	2.5293E+03	2.5293E+03	2.5744E+03	2.4855E+03	2.5780E+03	2.5299E+03	2.5293E+03	2.5324E+03	2.5293E+03	2.5353E+03
	STD	6.2106E-11	3.0402E+01	2.9718E-05	3.0605E+00	2.0355E-06	2.2559E+01	4.0771E-04	3.7559E+01	8.4815E-01	0.0000E+00	3.1789E+00	4.6751E-12	2.7219E+01
	RANK	5	11	7	2	6	12	1	13	8	2	9	4	10
F10	AVG	2.5677E+03	2.5660E+03	2.5044E+03	2.5173E+03	2.5705E+03	2.5075E+03	2.5037E+03	2.5803E+03	2.5086E+03	2.5895E+03	2.5408E+03	2.5403E+03	2.5553E+03
	STD	5.7450E+01	6.6405E+01	2.1562E+01	0.0000E+00	6.3037E+01	2.7662E+01	8.1881E+00	6.1001E+01	3.0720E+01	1.1776E+02	8.6871E+01	6.7993E-02	5.9515E+01
	RANK	4	10	2	6	11	3	1	12	5	13	8	7	9
F11	AVG	2.8267E+03	2.9933E+03	2.7057E+03	2.9000E+03	2.8965E+03	2.8812E+03	2.8788E+03	2.9242E+03	2.7375E+03	2.8350E+03	2.8904E+03	2.6000E+03	2.8103E+03
	STD	1.4126E+02	1.5182E+02	1.2645E+02	4.0778E+01	2.7825E+01	1.6642E+02	4.6744E+01	2.2797E+02	1.9374E+02	1.1605E+02	5.4811E+01	6.3044E-05	1.4122E+02
	RANK	5	13	2	11	10	8	7	12	3	6	9	1	4
F12	AVG	2.8607E+03	2.8682E+03	2.8692E+03	2.8633E+03	2.8925E+03	2.8697E+03	2.8983E+03	2.8708E+03	2.8637E+03	2.8670E+03	2.8676E+03	2.8607E+03	2.8676E+03
	STD	1.6945E+00	7.3574E+00	3.3280E+00	0.0000E+00	1.5721E+01	1.6170E+00	4.5280E+00	9.2798E+00	1.6075E+00	9.4473E+00	1.8946E+00	1.7485E+00	8.4760E+00
	RANK	1	8	9	3	12	10	13	11	4	5	7	2	6

For Function F2, the algorithm recorded an average of $4.0296E+02$ with a standard deviation of $3.6812E+00$, achieving the best rank of 1. This indicates that HGWMPA is well-equipped to handle functions requiring precise optimization. In Function F3, HGWMPA maintained competitive performance with an average of $6.0004E+02$ and a rank 6. Function F4 demonstrated similar strengths, where HGWMPA achieved an average of $8.0736E+02$ and secured the top rank. This trend of high performance continued with Function F5, where the algorithm achieved an average of $9.0014E+02$ and ranked 3rd, showcasing its adaptability across diverse functions.

The next set of functions, F6 to F8, presented more complex optimization challenges. For Function F6, HGWMPA achieved an average of $1.8004E+03$ with a standard deviation of $1.4303E-01$, ranking 1st. This result emphasizes the algorithm's capability to effectively find optimal solutions in challenging scenarios. In Function F7, the algorithm recorded an average of $2.0076E+03$ with a standard deviation of $8.4019E+00$, again securing the top rank. This consistency in performance indicates that HGWMPA is highly reliable when navigating complex optimization landscapes. Function F8 continued this trend, achieving an average of $2.2067E+03$ and ranking 2nd, showcasing its robust optimization capabilities.

Lastly, the group encompassing functions F9 to F12 demonstrated HGWMPA's strong performance across optimization scenarios. In Function F9, HGWMPA achieved an average of $2.5293E+03$ with a standard deviation of $6.2106E-11$, ranking 5th. This result highlights its competitive performance among various optimization algorithms. For Function F10, the algorithm recorded an average of $2.5677E+03$ with a standard deviation of $5.7450E+01$, securing the rank of 4. In Function F11, HGWMPA achieved an average of $2.8267E+03$ with a standard deviation of $1.4126E+02$, ranking 5th, demonstrating its adaptability and reliability in diverse optimization tasks. Finally, in Function F12, HGWMPA maintained strong performance with an average of $2.8607E+03$ and a rank of 1, further solidifying its position as an effective optimization tool.

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