Research on Site Selection and Path Planning for Straw Recycling Centers Based on a Mixed Particle Swarm Algorithm

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Abstract: The low-carbon utilization of straw is a crucial strategy for enhancing the rural ecological environment and achieving the "dual carbon" goals in agriculture. However, the recovery of straw encounters several challenges, including high transportation costs, unstandardized collection and storage practices, and the absence of a scientific management and planning system. To address these issues, this paper integrates location and routing planning problems and develops a mixed-integer programming model for an agricultural straw resource utilization network location-routing (LRP) with the objective of minimizing transportation costs associated with straw recovery. Given that the problem presented in this paper is classified as NP-hard, a hybrid particle swarm optimization algorithm is designed, leveraging the strengths of both particle swarm optimization and genetic algorithms. The effectiveness of this algorithm is validated through benchmark case testing. Utilizing simulation cases and considering the characteristics of straw resource utilization, optimal solutions for the facility location and vehicle routing planning within the agricultural straw resource utilization network are achieved. The study demonstrates that the model can significantly reduce transportation costs and standardize the transportation system. Furthermore, the findings contribute to the advancement of agricultural reverse logistics and hold substantial practical significance.

Keywords: Straw Recycling; Hybrid Particle Swarm; Optimization Path; Reverse Logistics

1. Introduction

The comprehensive utilization of straw not only facilitates emission reduction and carbon sequestration but also promotes the industrial development of straw, which can enhance agricultural income, improve farmers' efficiency, and support rural revitalization. The traditional methods for straw disposal include incineration and natural return to the field. Straw incineration not only releases a significant amount of black carbon particles, nitrogen oxides, sulfur dioxide, carbon dioxide, carbon monoxide, and polycyclic aromatic hydrocarbons (PAHs), but it also represents a considerable waste of resources. Hong et al. [1] studied the environmental impact of corn straw utilization and concluded that straw burning significantly increased the environmental burden in grain-producing regions such as Henan and Shandong. Since 1999, China has implemented a policy banning straw burning. In the research conducted by Wu et al. [2], it was found that, under the influence of two major straw burning ban policies enacted in 2013 and 2016, the total greenhouse gas emissions from crop residue open burning (CROB) in China were reduced by 31.2% from 2012 to 2021.However, the straw burning ban does not fundamentally resolve the issue. The country is actively exploring comprehensive utilization of straw. As a major agricultural nation, fully utilizing straw resources could significantly alleviate the pressure on energy and the environment in China. Shi et al. [3] found that converting unnecessary crop straw utilization (e.g., for cooking and heating, open burning, and other activities) into bioenergy in 2021 could prevent the emission of 122 metric tons of greenhouse gases, while substituting the corresponding fossil fuels with bioenergy could further reduce emissions by an additional 34 to 86 metric tons. Simultaneously, Koul et al. [4] demonstrated that developing bioenergy is an effective strategy for reducing greenhouse gas emissions and achieving sustainable utilization of crop straw.

Biomass energy is regarded as a promising alternative energy source to meet future energy demands and facilitate decarbonization efforts. Agricultural by-product straw is one of the key raw materials for biomass energy production. Research conducted by Fang et al. [5] indicates that if all three types of straw (corn, wheat, and rice) are utilized for bioenergy production, the potential output by 2030 could reach 75.1 million tons of electricity, 151.5 million tons of bioethanol, 182.1 million tons of biomethane, and 329.1 million tons of renewable fuels. Bioenergy has emerged as the fourth largest energy source in China, following coal, oil, and gas, accounting for 3.6% of the country's total energy supply in 2018 and 30.9% of the overall renewable energy supply [6].

In recent years, several scholars have conducted research focused on enhancing the collection, storage, and transportation systems for straw recycling. For instance, Mao et al. [7] developed an Internet of Things (IoT) intelligent monitoring system tailored to the straw recycling process at the stage when straw is removed from the field, which significantly improves the conversion rate of the straw recycling system. Liu et al. [8] employed an ant colony algorithm to analyze the pathways for preliminary straw recycling off the ground, taking into account both the mechanical pathways and operational conflicts associated with straw recycling, thereby increasing the efficiency of mechanical recycling. During the stages of straw storage and transportation, Mao et al. [9] applied migration theory and a dual-objective mixed-integer model to investigate biomass energy recovery from straw, enhancing system efficiency through effective planning and design of the supply chain. Table 1 summarizes pertinent research in the field of LRP and straw recycling.

Table 1. Characteristics of Relevant Literature

Literature	Research phase	Straw Recycling	Research Objectives:	Solution
Mao et al. [7]	Straw off the field	√	Enhance the Efficiency of Straw Recycling	Genetic algorithms
Liu et al· [8]	Straw off the field	√	The Shortest Path	Ant colony algorithm
Mao et al· [9]	Storage and transportation stage	√	Minimal Shipping Costs	Immune algorithm
Liu et al· [10]	Straw transportation	√	The transportation process has a minimal carbon footprint.	Mathematical modeling
Zhu et al· [11]	Site selection of storage sites	√	The construction and transportation costs of the storage station are minimal.	Integer nonlinear programming
Liu et al· [12]	Storage and transportation stage	√	Balance the costs of raw material storage and transportation with energy transmission losses.	Co-programming simulation analysis
Ma et al· [13]	Recycling center site selection - path planning	×	The overall cost of the recycling system is minimal.	Genetic algorithms
Wang et al· [14]	Garbage collection and transportation stage	×	Minimal Shipping Costs	Genetic algorithms
This paper	Site selection and path planning of storage points	√	Minimal System Operating Costs	Hybrid algorithm

The aforementioned studies focus on various stages of straw recycling; however, there remains a relative scarcity of research aimed at standardizing the straw recycling system. This paper introduces the site-path (LRP) theory to address the challenges associated with the high transportation costs of straw recycling and the unscientific selection of recycling facility locations. By integrating site selection and path optimization for straw recycling facilities, we develop a county-level, three-tier recycling network location-path (LRP) optimization model. A mixed meta-heuristic algorithm is employed to optimize the straw recycling network. The findings of this study are significant for reducing the operational costs of related reverse logistics networks and enhancing the overall efficiency of the organization. The main contributions of this study can be summarized in three key points.

(1) Taking the three-tier straw recycling network at the county level as the focus of optimization, this study primarily investigates the selection of locations for straw recycling facilities and the optimization of transportation routes, thereby broadening the research perspective.

(2) In the context of the LRP problem, an optimization model for the straw recycling network is developed. This model addresses the location of facilities and the planning of transportation vehicle routes in a unified manner, adhering to the same constraints. This approach enhances the consistency of related decision-making processes.

(3) According to the established model, a more accurate and targeted hybrid particle swarm optimization algorithm has been designed by

integrating the advantages of genetic algorithms and particle swarm optimization. This approach aims to enhance both the efficiency and accuracy of solutions.

2. Problem Description and Model Building

2.1 Problem Description

The focus of this study was a specific type of agricultural straw, and other straw types were not addressed within the model. From a micro perspective, a three-tier recycling network at the county level was developed, and the transportation routes were systematically selected and optimized to minimize the costs associated with straw recycling. The research problem and optimization objective can be characterized as the features of the Location Routing Problem (LRP) within the straw recycling network. Specifically, the single optimization goal is to clarify the demand-supply characteristics, which include a single facility, a single mode of transportation, unlimited facility capacity, no time constraints, and cost minimization [15,16].

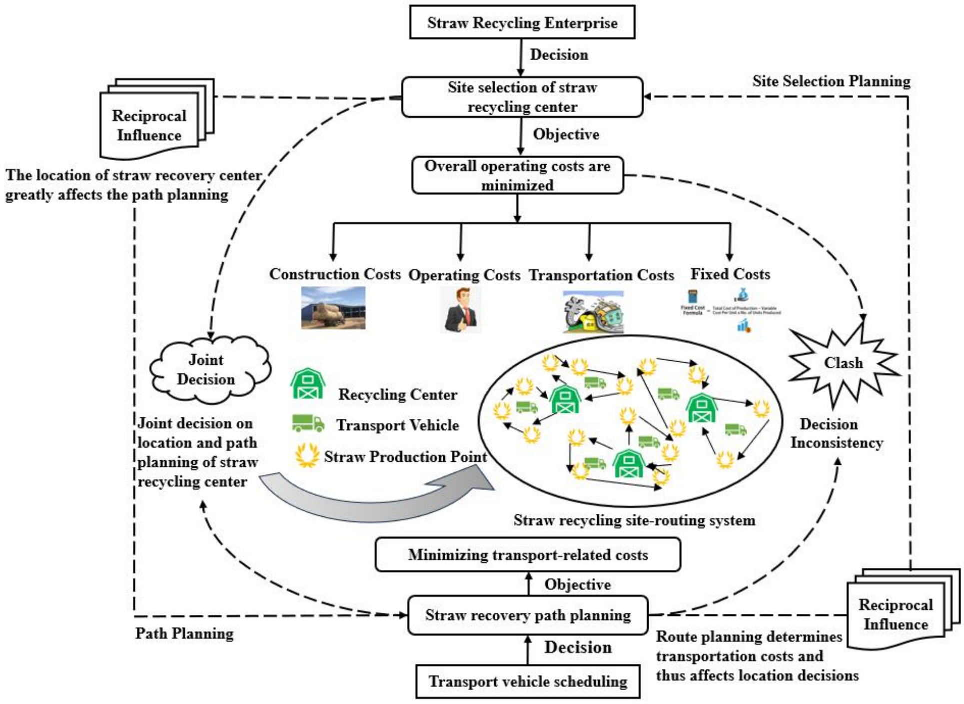

Figure 1. Straw Recovery System Clash

As illustrated in Figure 1., the research question can be articulated as follows: The costs associated with straw recycling encompass the construction and operational expenses of recycling facilities, as well as the transportation costs for straw recycling. Additionally, the location and route planning of the straw recycling center significantly influence the overall operating costs of the system. Once the location of the alternative straw recycling center is established, the construction scale and recycling routes for the facilities at each site are determined to minimize the system's operating costs and enhance the consistency of site-based planning decisions.

2.2 Model Assumptions

Murray and Chu [17] pointed out that the Facility Location and Transportation Scheduling Problem (FSTSP) is an NP-hard problem. The Location Routing Problem (LRP) proposed in this paper is an extension of the FSTSP and is also classified as NP-hard. The LRP encompasses two sub-problems: the Location Allocation Problem (LAP) for facility siting and the Vehicle Routing Problem (VRP) for path optimization. When addressing LRP challenges, it is often impractical to derive exact solutions directly. Therefore, it is necessary to establish certain assumptions regarding the conditions and environment of the constructed model to enhance its feasibility and practicality, making it more convenient to solve and adaptable. Based on the relevant algorithm and the actual situation, the following assumptions are made regarding the model.

(1) There are no restrictions on the types of vehicles used to transport straw; however, the vehicle models employed at various collection points are consistent.
(2) The location of the candidate straw collection point is established, and the straw generated at the source can only be transported to this collection point.
(3) Each vehicle services multiple straw generation points until it reaches maximum load capacity.
(4) The specifications of the transport fleet at each straw collection point are uniform. The standard load capacity of a 16-meter flatbed truck is 31 tons. Given the substantial volume of straw, it is assumed that the maximum load limit for the transport fleet is 50 tons.
(5) Assuming that the transportation cost per unit distance is known and remains constant, the total calculated cost encompasses vehicle transportation costs, depreciation expenses, and labor costs.
(6) The entire recycling network is functioning normally, unaffected by weather conditions, road conditions, accidents, or other factors.
(7) The collection and compression of straw at the generation point are operating smoothly, with transportation scheduled at a consistent time, without accounting for the impact of loading and unloading durations.

2.3 Symbol Explanation and Modeling

Table 2 presents the symbols and definitions of the parameters used in the model.

Table 2. Symbols and Definitions of Model Parameters

Symbol	Definition
M	Represents a collection of potential straw collection points $M = \{s \mid s = 1, 2, \cdots, S\}$
N	Represents the set of all straw production points $N = \{i \mid i = S+1, S+2, \cdots, S+N\}$
G	Represents the sum of potential straw collection and production points $G = M + N$
V	Represents a collection of transport vehicles K that can reach the route of the collection point $V = \{v_k \mid k = 1, 2, \cdots, K\}$
F_s	Represents $s(s \in M)$ the fixed cost of setting up a straw collection point at the location
C_{ij}	Represents the cost of transportation per unit distance i from point j to point, including to the straw collection point（$i\ j \in G$）
d_{ij}	Represents the distance i from the service point to the service point j, including to the straw collection point（$i\ j \in G$）
q_j	Represents the amount of straw produced by j the service point
Q_k	Indicates the loading capacity of the K transporter
W_s	Represents the s average operating cost of the straw collection points established at the location
X_{ijk}	The decision variable, 1 indicates that the i first transporter j from the service point to the service point k includes the collection point, 0, and the other
Z_s	Decision variables, 1 means that a collection point is created at an alternate address, and 0 is other

The following outlines the fundamental problem and presents the LRP problem model.

$$MinF = \sum_{i \in G} \sum_{j \in G} \sum_{k \in V} C_{ij} q_j d_{ij} X_{ijk} + \sum_{s \in M} (F_s + W_s)\ Z_s \quad (1)$$

Eq. (1): $MinF$ is the cost objective function $\sum_{i \in G} \sum_{j \in G} \sum_{k \in V} C_{ij} q_j d_{ij} X_{ijk}$ Indicates the cost of transportation, $\sum_{s \in M} (F_s + W_s)\ Z_s$ and indicates the construction and operating costs of agricultural straw collection points.

$$\sum_{k \in V} \sum_{i \in G} X_{ijk} = 1, \forall j \in N \quad (2)$$

Eq. (2) indicates that there is a limit of one transport fleet service per production point.

$$\sum_{j \in G} q_j \sum_{i \in G} X_{ijk} \le Q_k, \forall k \in V \quad (3)$$

Eq. (3) indicates that the total number of straws on each recycling transport route does not exceed the carrying capacity.

$$\sum_{i \in G} X_{ipk} - \sum_{j \in G} X_{pjk} \ge 0, \forall k \in V, p \in G \quad (4)$$

Eq. (4) ensures the spatial continuity of the recovery route.

$$\sum_{r \in M} \sum_{j \in N} X_{rjk} \le 1, \forall k \in V \quad (5)$$

Eq. (5) indicates that each recycling route departs from a maximum of one agricultural straw collection point.

$$\sum_{k\in V} X_{smk} + Z_s + Z_m \le 2, \forall s, m \in M \quad (6)$$

Eq. (6) indicates that there is no connection between agricultural straw collection points.

$$\sum_{k\in V}\sum_{j\in N} X_{sjk} - Z_s \ge 0, \forall s \in M \quad (7)$$

Eq. (7) ensures that the starting point of each transport vehicle recycling transportation route is the agricultural straw collection point.

$$\sum_{j\in N} X_{sjk} - Z_s \le 0, \forall k \in V, s \in M \quad (8)$$

Eq. (8) ensures that each transport vehicle can only have one agricultural straw collection point as the starting point for the recycling transportation route.

$$\sum_{s\in M}\sum_{i\in N} X_{sjk} + \sum_{j\in N}\sum_{m\in M} X_{jmk} \le 1, \forall k \in V \quad (9)$$

Eq. (9) ensures that any two agricultural straw collection points are not on the same recycling transport route.

$$X_{ijk} = 0 or 1, \forall i, j \in G, k \in V \quad (10)$$

$$Z_s = 0 or 1, \forall s \in M \quad (11)$$

Eq. (10) and Eq. (11) ensure that the integer constraint is satisfied.

3 Solving Algorithms

3.1 Hybrid Particle Swarm Algorithm

The crossover and mutation operations in genetic algorithms are integrated into particle swarm optimization to prevent the latter from converging on local optimal solutions. Simultaneously, the adaptability and robustness of genetic algorithms enable rapid adjustments to changes in the target [18,19].

3.1.1 Individual code

If there are m straw collection points represented by 1 and 2, ..., m, and n straw production points are represented by m+1, m+2, ..., m+n, and the chromosome sequence grows into m+n, and the sequence must be a straw collection point, and the entire chromosome must include all the straw production points. For example, if there are 2 straw collection points and 8 straw production points, 1→10→5→4 represents the recycling route for collection point 1, and 2→6→9→3→7→8 represents the route for collection point 2 can be represented as shown in Figure 2.

1	10	5	4	2	6	9	3	8	7

Figure 2. Chromosome Example

3.1.2 Construct the initial solution

The algorithm employs a greedy strategy to construct an initial solution, which involves selecting the option that appears to be optimal at each step, irrespective of the long-term consequences [20,21]. When formulating an initial solution, the greedy strategy can opt for the choice that currently offers the maximum benefit or minimizes the cost, based on the specific objective function and constraints. For instance, in the traveling salesman problem, one might choose to visit the nearest unvisited city from the current location at each step. In the knapsack problem, the strategy would involve selecting the item with the highest unit value per weight to include in the backpack at each iteration.

3.1.3 Particle crossing

The selected particles are chosen through a roulette mechanism and updated by crossing with both individual and group extremums. The overall logic is continuously detected and adjusted until there are no position conflicts, as illustrated in Figure 3.

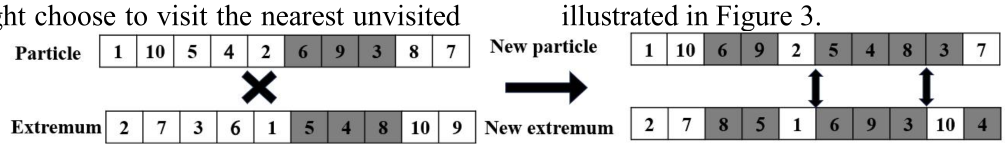

Figure 3. Mechanism of Particle Crossing.

3.1.4 Particle Variation

After the crossover process, some particles undergo a mutation operation. This mutation is achieved by randomly exchanging the numbers within the particles. For example, as illustrated in Figure 4, the numbers in positions 3 and 8 are swapped to generate new particles.

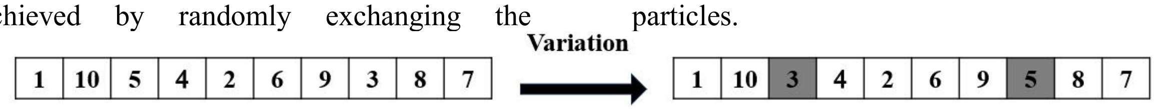

Figure 4. Variation Operation

3.2 Algorithm Implementation

The specific steps of the HGAPSO algorithm proposed in this study to address the straw recycling path planning problem are outlined as follows:

Step 1: Input the pertinent location details of both the straw collection point and the production point to create a distance matrix.

Step 2: Set the algorithm parameters, allocate the straw generation points based on distance, and employ a greedy strategy to construct the initial solution.

Step 3: Update the inertia weight, learning factors, particle positions, and fitness values.

Step 4: Update the particles by selecting particle crosses and mutations using a roulette selection method.

Step 5: Calculate the fitness value of each particle, compare the advantages and disadvantages of the particles, and retain the best-performing particles.

Step 6: Update the optimal position of the entire particle swarm and document the trajectory.

Step 7: Check if the current number of iterations has reached the maximum limit. If it has, the algorithm terminates and outputs the optimal transport path. If not, proceed to Step 3.

4. Mock Cases

4.1. Case Description

In the notice of the General Office of the Ministry of Agriculture and Rural Affairs on doing a good job in the comprehensive utilization of crop straw in 2023, Taikang County in Henan Province is one of the cities and counties with large straw resources. Taikang County is between 33 54'~34 17'N, 114 32'~115 08'E, there are 23 townships, on this basis, 23 straw production points are established, and the latitude and longitude coordinates of the township people's government are the coordinates where the production points are located. After the coordinate transformation, that is, the Cartesian coordinate system was established with 34 N latitude and 114 E as the origin, and the decimal part was magnified 100 times to generate two-dimensional coordinates, and the location coordinates of the four straw recovery points were known. Due to the different straw collection capacity of each straw production point, the number of straw at each straw production point was simulated by random number, and the relevant coordinates and yield data of straw production point and collection point are shown in Table 3. The relative position is represented in Figure 5.

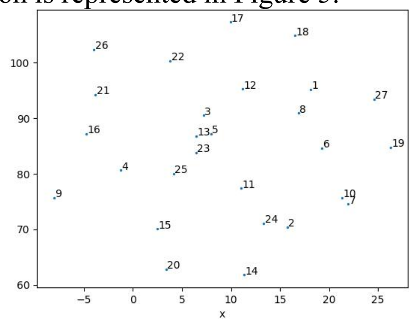

Figure 5. Relative Position of the Straw Collection Point and the Production Point

Table 3. Data on Straw Recycling Network Facilities

Numbering	Recycle the facility	Latitude	Longitude	X coordinates	Y coordinates	Amount of straw produced (t).
1	Collection Point 1	34.181	114.952	18.115	95.155	0.000
2	Collection Point 2	34.157	114.704	15.735	70.374	0.000
3	Collection Point 3	34.718	114.905	7.177	90.507	0.000
4	Collection Point 4	33.988	114.806	-1.123	80.630	0.000
5	Rural areas	34.080	114.872	7.972	87.236	17.470
6	Wangji Township	34.193	114.846	19.290	84.602	16.230
7	Gaoxian Township	34.220	114.745	21.966	74.529	13.750
8	Yangmiao Township	34.169	114.909	16.880	90.909	18.710
9	Wulikou Township	33.919	114.757	-8.081	75.731	12.180
10	Sesame Valley	34.213	114.757	21.315	75.731	17.570
11	Dutang Township	34.111	114.774	11.059	77.381	16.580
12	Gaolang Township	34.112	114.952	11.184	95.220	15.340
13	Cheng	34.064	114.868	6.426	86.799	12.750
14	Changying Town	34.113	114.618	11.330	61.830	11.490

15	Sunmukou Town	34.025	114.701	2.472	70.068	13.540
16	Old mound town	33.952	114.872	-4.777	87.216	15.570
17	Zhukou Town	34.099	115.073	9.925	107.269	13.570
18	Matou Town	34.165	115.048	16.533	104.839	15.700
19	Longqu Town	34.263	114.848	26.314	84.760	14.850
20	Ban	34.034	114.629	3.366	62.865	16.760
21	Fu Caolou Town	33.962	114.942	-3.823	94.219	17.030
22	Machang Town	34.038	115.003	3.792	100.349	11.220
23	Maozhuang Town	34.065	114.838	6.452	83.791	16.630
24	Qingji Town	34.133	114.711	13.345	71.112	11.910
25	Daxu Zhai Town	34.041	114.800	4.123	79.996	15.340
26	Zhangji Town	33.960	115.024	-3.975	102.381	13.690
27	Transfer to the town	34.246	114.934	24.578	93.369	18.060

The four straw collection points are represented by the natural numbers 1 to 4, while the 23 straw production points are numbered sequentially from 5 to 27. The unit transportation cost is $C_{ij} = 0.015 \text{yuan} / \text{km} \cdot \text{kg}$, along with the construction and operating costs of the agricultural production waste collection points, is detailed in Table 4. This includes specific expenses such as salaries for managers and staff, equipment maintenance, daily operational costs of the collection points, equipment expenditures, and fixed equipment costs.

Table 4. Construction and Operating Costs of Straw Collection Points

Straw collection points	Chromosomes encode sequence numbers	Construction and operating costs (Wr+Fr)/yuan
1	1	160000
2	2	220000
3	3	152000
4	4	183000

4.2 Algorithm Performance Analysis

To evaluate the performance of the Hybrid Genetic Algorithm Particle Swarm Optimization (HGAPSO) in solving the siting-path planning model, it is compared with the standard particle swarm optimization and genetic algorithms across three dimensions: convergence speed, solution accuracy, and computational complexity. To ensure comparability, the population size and the number of iterations are kept consistent. Based on relevant literature, the population size is set to 50, and the algorithm is run for 500 iterations. The optimal solution is determined from 20 runs, as presented in Table 5, while the effects of the algorithm iterations are illustrated in Figure 6.

Table 5. Comparison of the Optimal Results of the Three Algorithms

Comparison items	HGAPSO	GA	PSO
Transportation cost/yuan	138185.4	146533.8	148922.9
Iteration time/s	18.70	57.46	9.32

As illustrated in Figure 6, the convergence of HGAPSO begins around the 50th generation, while the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithms start to converge around the 100th generation. Notably, the final convergence result of HGAPSO is smaller than that of both the GA and PSO algorithms, indicating that the convergence performance of HGAPSO is better。 In terms of algorithm complexity, since the complexity of genetic algorithm depends on the number of calls of the fitness function, and the number of calls is related to population size, iteration number, crossover rate and mutation rate, particle swarm algorithm is related to inertia weight, self-awareness factor and social cognitive factor. Since these parameters are all externally given, HGAPSO constructs the initial solution by adding a greedy strategy without adding other complex operations, so the algorithm complexity does not change. Taking into account all aspects, HGAPSO can solve the problem of straw recycling site selection path in a feasible and effective way.

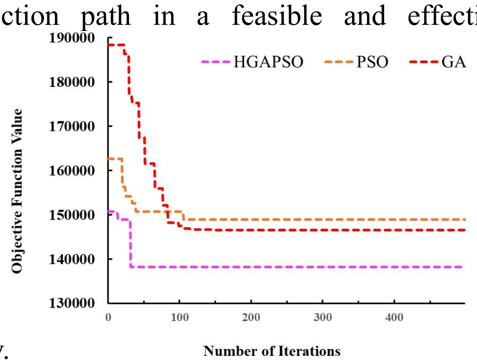

Figure 6. Comparison Chart of Algorithm Iterations

4.3. Solve the Result

The traditional transportation scheme involves randomly arranging transportation routes between nearby straw generation points. Alternatively, routes can be planned based on the shortest transportation distance, maximizing the amount transported while satisfying transportation requirements. In this context, the hybrid particle swarm optimization algorithm is employed to optimize transportation distance as the primary objective. After validating the accuracy and effectiveness of the hybrid particle swarm optimization algorithm, it is utilized for site selection and path planning. The results are then compared with the transportation routes generated by the traditional method, as illustrated in Table 6.

Compared to the traditional method, which aimed to minimize transportation distance, the total transportation cost was reduced by 16,410.35 yuan, representing a decrease of 10.6%. Additionally, when compared to the random arrangement transportation scheme, the transportation cost decreased by 22,477.14 yuan, or 14.0%. The optimization scheme utilizing hybrid particle swarm optimization significantly lowered the transportation costs associated with straw recycling. The transportation costs for the four distribution centers were 39,419.61 yuan, 36,516.14 yuan, 36,675.86 yuan, and 25,573.92 yuan, respectively.

Table 6. Optimization Results

How decisions are made	Transport routes	Transportation distance (km)	Transported volume (tons)	Total transport distance (km)	Total Transportation Cost (RMB)
Traditional method (random route).	1-17-18-27-1	42.38	47.33	264.47	160662.70
	1-8-6-19-1	31.44	49.79		
	2-10-7-2	16.60	31.32		
	2-14-11-24-2	34.33	39.98		
	3-5-23-13-3	13.93	46.85		
	3-12-22-26-3	39.51	40.25		
	4-16-21-4	28.38	32.60		
	4-20-15-25-4	41.06	45.64		
	4-9-4	16.84	12.18		
Shortest transport distances	1-6-19-27-1	33.14	49.14	248.28	154595.87
	1-8-17-18-1	39.05	47.98		
	2-7-10-11-2	27.67	47.90		
	2-14-20-24-2	33.09	40.16		
	3-21-26-22-3	38.21	41.94		
	3-5-23-13-3	13.93	46.85		
	3-12-3	12.38	15.34		
	4-25-15-9-4	35.85	41.06		
	4-16-4	14.96	15.57		
Minimal cost	1-19-27-1	28.73	32.91	276.74	138185.50
	1-8-6-1	21.79	34.94		
	1-18-17-1	31.47	29.27		
	2-11-20-2	39.32	33.34		
	2-10-7-24-2	20.88	43.23		
	2-14-2	19.22	11.49		
	3-21-26-22-3	38.21	41.94		
	3-13-23-5-3	13.93	46.85		
	3-12-3	12.38	15.34		
	4-25-15-9-4	35.85	41.06		
	4-16-4	14.96	15.57		

In the initial phase of establishing straw collection points, the construction scale can be modified based on the number of service straw production points and the volume of straw collected at each collection point. The amounts of straw recovered are 97.12, 88.06, 104.13, and 56.63 tons, respectively. Therefore, the construction scale for Collection Point No. 3 should be the largest, while Collection Point No. 4 should be the smallest. The optimal transport route for the straw recycling system is illustrated in Figure 7.

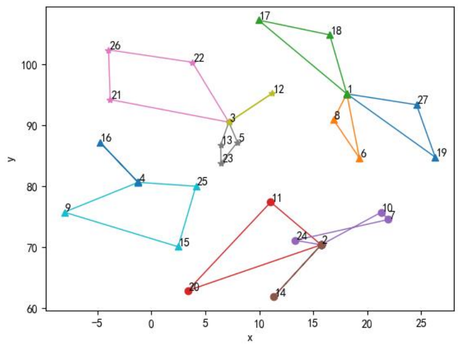

Figure 7. The Optimal Transportation Route

5. Conclusion

The research findings presented in this paper address several critical issues, including the high transportation costs associated with straw recovery, non-standardized collection and storage operations, and the absence of a scientific management planning system. These findings provide essential prerequisites for the industrial development of straw and contribute to achieving the agricultural "double carbon" goal. The research conclusions are summarized in the following three aspects.

(1) This paper aims to expand the existing mathematical model for optimizing straw transport paths. Given the high costs associated with straw transportation and the county recovery network, the study investigates strategies to minimize transportation expenses during the storage and transport stages of straw. The findings of this research can significantly lower the costs related to straw recovery and transportation.

(2) The hybrid particle swarm optimization algorithm developed for this model leverages the strengths of both the standard genetic algorithm and the particle swarm optimization algorithm. This approach not only ensures a rapid solution speed but also yields superior optimization results.

(3) The model developed in this paper, along with its solution algorithm, is highly applicable and can be extended to other related studies to advance the practical theory of rural reverse logistics. For instance, it can be utilized for site selection and transportation path planning of agricultural products, as well as for optimizing the transportation paths for rural domestic waste, among other applications.

In summary, this paper offers decision support for the location and route planning of straw recycling centers. However, there are some limitations; specifically, multi-vehicle recycling and associated environmental impacts have not been addressed. These areas will be the focus of future research.

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