Study on the Optimization of Agricultural Production Waste Recycling Network under the Concept of Green Cycle Development

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Abstract: This study is based on the concept of converting agricultural waste into green new energy, we combine the concept of green cycle development and the relevant theories in modern system engineering to optimize the study of agricultural production waste recycling network. In this paper, the optimization of the agricultural production waste recycling network is divided into two aspects—facility site selection and vehicle path planning—with the objectives of agricultural production waste green recycling and the minimization of system construction and operational costs. In this study, the site selection and path planning problems were unified and an optimization model for the agricultural production waste recycling network site-path (LRP) problem was constructed. The optimization results of agricultural production waste recycling network facility location and recycling vehicle path planning were obtained by using the simulation data in the optimization model and designing the genetic algorithm design with the relevant characteristics of agricultural production waste recycling. The feasibility and operability of the model were verified through experiments. The research related to the optimization of agricultural production waste recycling networks can be used to both reduce production costs in agricultural areas and progress the practical theory of reverse logistics in agricultural areas. Agricultural waste resource utilization provides important support for the development of an ecological agriculture cycle and helps protect the environment.

Keywords: agricultural production waste recycling; green cycle development; site-path problem; genetic algorithm; reverse logistics

1. Introduction

Recently, under the main umbrella of the green and sustainable development of modern agriculture, the level of agricultural production has been improving year by year, as has economic development in agricultural areas; however, the rapid increase in agricultural production levels and the accompanying extensive planting of high-tech crops have caused serious pollution problems in rural areas. Waste is an unavoidable byproduct of most human activity. It is an unavoidable non-product output of agricultural production and the agricultural population in terms of both their production and life. The output of this type of waste is huge in quantity, diverse in type, widely distributed and scattered, with a small amount of waste being generated in each place. These factors are problematic for the recycling of agricultural production waste. In particular, the treatment of this type of waste, when inappropriate, untimely, and unscientific, leads to pollution in the natural environment and seriously hinders the development process of green agriculture [1–6]. General Agricultural production waste treatment technologies mainly include:
1. High-temperature aerobic composting technology: the process of using microorganisms to degrade organic matter in waste, consisting of pre-treatment, main fermentation, post-fermentation, post-treatment and storage. It can make the waste achieve the purpose of harmless and reduction, and increase the content of soil organic matter.

2. Biomass gasification technology: the process of using organic waste resources such as rural straw, firewood and hulls, pitching and burning to produce combustible gas. It has the characteristics of easy to use and low cost.

3. Earthworm composting technology: The process of further digestion of organic solid waste treated by a certain degree of fermentation by using the characteristics of earthworms that eat decay, have a wide range of food, eat a large amount of food and their digestive tract can secrete a large number of enzymes. To make the rural household waste harmless, reduce and resourceful.

4. Anaerobic fermentation technology: the process of producing biogas by microbial fermentation of organic matter in an anaerobic environment. It can convert human and livestock manure as the main pair of organic matter into energy to be used as living fuel, so that the organic matter is fully resourceful. It has the advantages of resourcefulness of waste, convenient management, low investment, easy operation, etc., and is easy to be promoted and used in the majority of rural areas.

Therefore, the establishment of an efficient agricultural waste recycling network can play a positive role in solving environmental pollution and alleviating resource constraints, thus promoting the development of ecological agriculture and the healthy and sustainable development of agricultural resources, and helping to achieve the goal of “carbon peaking and carbon neutrality”. Reasonable and scientific planning of the location of waste collection offices and treatment stations can help reduce the construction costs of waste recycling infrastructure in rural areas. Moreover, the optimal design and management of recycling routes for the vehicles involved can help to reduce equipment maintenance costs and vehicle recycling and transportation costs. In addition, it can improve the operation and management efficiency of agricultural production waste recycling systems and decision-making in agricultural production waste recycling network optimization. The optimal design of the agricultural waste recycling network can improve the decision-making level [7–11].

In terms of the analysis of total agricultural production waste generation and value potential, Tamilselvi concluded that agricultural production waste contains good materials for the preparation of capacitive materials and has recyclable value [12]. Antic demonstrated that the use of livestock manure and plant straw in crop production can reduce the use of herbicides, fertilizers, and pesticides, thus reducing harmful substance residues in animals [13]. Jaffar collected biomolecules such as cellulose, hemicellulose, and lignin from agricultural production waste and four different agricultural wastes to study methanogenesis and demonstrated the energy value in agricultural production waste [14]. In the study of waste recycling network facility location optimization, Jayaraman referred to the 0–1 integer programming model in solving the facility point location problem in reverse logistics and achieved good accuracy [15]. Ralf studied a two-level recycling network structure, including recycling sites and consumers in the recycling network of waste vehicles, and constructed a related optimization model combined with a heuristic algorithm to solve it [16]. In the study of vehicle path optimization in waste recycling networks, the two-stage heuristic algorithm designed by Rahmani exhibited reliable research prospects and potential in the field of unified logistics network transport vehicle path planning and facility location optimization [17]. Huang considered the recycling stage of reverse logistics or the production process as a whole system problem, adding constraints related to greening and constructing a relevant reverse logistics model [18].

At present, research on agricultural production waste recycling mainly focuses on the resourceization of agricultural production waste, and the necessity of recycling agricultural production waste is argued from the point of view of its resource content and value
potential. However, there is little attention paid to the siting of recycling facilities and transportation vehicle path optimization, and the following problems exist:

1. Distinguishing research on site optimization from path optimization is difficult, which reduces the effectiveness of recycling network integration;
2. The research is simple at the theoretical level and lacks consideration of the characteristics of agricultural production waste generation, which makes the theory less practical;
3. The research on facility data and the transportation routes of the agricultural production waste recycling network and their dynamic changes needs to be deepened.

Therefore, introducing LRP theory and using the heuristic algorithm for rural reverse logistics network optimization is of great significance in terms of improving the reverse logistics theory and the level of the related research. Our research findings are of great significance in terms of reducing the operating costs of reverse logistics networks and improving the efficiency of organizational operations. This paper explores whether LRP has a universally applicable algorithm in rural reverse logistics network optimization. Moreover, it aims to demonstrate the feasibility of agricultural waste recycling on the basis of combining the site-path problem with the relevant characteristics of agricultural production reverse logistics to provide a relevant theory for the unified site-path optimization of the agricultural production waste recycling network. The aim of this study was to provide a theoretical approach to the unified optimization of the location path of agricultural production waste recycling networks based on the feasibility of agricultural waste recycling.

The main contributions and innovations of the paper are.

1. A three-level optimization model for agricultural production waste recycling network is constructed, and it focuses on the optimization problems of recycling facility siting and transportation vehicle path planning in the recycling network.
2. The optimization model of agricultural production waste recycling network is constructed in the context of the LRP problem, and the siting and transportation vehicle path planning are solved uniformly under the same constraints to improve the uniformity of the model.
3. Decimal natural number coding is used to encode the facility points of agricultural production waste recycling network, bring in optimization information such as site selection and path planning when solved by genetic algorithm, and add adaptive operators to improve the efficiency and accuracy of the solution and derive an optimization scheme.

Conducting research on the aspects related to the optimization of agricultural production waste recycling network can not only reduce the production cost in agricultural areas, but also enrich the practical theory of reverse logistics in agricultural areas.

2. Materials and Methods

Agricultural production waste can be divided into farming waste (livestock manure, etc.), planting waste (crop straw, crop residues), and waste generated by the use of other byproducts in the agricultural production process (pesticides, agricultural film, packaging waste). The object of this paper is a single species of agricultural production waste, and the types of agricultural production waste are not discussed in the model. The research problem and optimization objectives of this study can be seen as the characteristics of the agricultural production waste recycling network LRP problem, i.e., the defined demand supply characteristics, a single facility, a single means of transportation, no limited vehicle carrying capacity, no limited facility capacity, no time window, cost minimization as a single optimization objective, using data from the simulation.

2.1. Composition of Agricultural Production Waste Recycling Network

In this paper, the agricultural production waste recycling network structure is divided into three levels—the agricultural production waste generation point, the agricultural pro-
duction waste collection point, and the agricultural production waste treatment point—as shown in Figure 1.

Figure 1. Composition of the agricultural production waste recycling network.

As can be seen from the schematic diagram, the agricultural production waste recycling system can be divided into two phases: the collection phase of agricultural production waste before the collection point and the transportation phase of agricultural production waste after the collection point. Therefore, the optimization of the agricultural production waste recycling network needs to be considered from two perspectives, i.e., the optimization of the waste recycling vehicle transportation route and the optimization of the location of the collection point.

2.2. Agricultural Production Waste Recycling Process

The first step is the agricultural production waste recycling stage. On the basis of the analysis of the characteristics and treatment methods of agricultural production waste, special vehicles travel to the agricultural production waste generation points in order to collect waste and transport it to the agricultural production waste collection points. This recycling network mainly consists of waste generation points and waste treatment points with known coordinate locations, wherein the coordinates and the number of alternative waste points are known (see Figure 2).

Figure 2. Specific recycling methods and processes for agricultural production waste.

The second step is the transfer stage. After the completion of agricultural production waste recycling, the agricultural production waste is transported from the collection point to the treatment point by the transport vehicle as there is a spatial distance between each
The third step is the classification and treatment stage. The waste is classified and treated at the agricultural production waste treatment point to realize the resourceization of agricultural production waste. In summary, the location of the collection and treatment points of agricultural production waste and the route planning of waste recycling and the transportation vehicles affect the operational efficiency and operational recycling costs of the whole recycling network. Thus, this needs to be studied in a reasonable and scientific manner. In the siting of the agricultural production waste recycling network, it is necessary to consider fixed costs, variable costs, natural conditions, the maximization of recycling, the production benefits, pollution emissions, and other issues and related indicators. In the siting of agricultural production waste recycling network facilities, it is necessary to focus on the fixed cost- and maintenance cost-related indicators. In the route planning of agricultural production waste recycling transportation vehicles, it is necessary to consider the vehicle transportation cost, the environmental economy, and other issues and related indicators. In the quantitative data, the vehicle transportation cost has a huge impact on the planning and scheduling arrangement decisions. Traditional waste recycling network optimization models solve the site-selection problem and path problem in two stages, which achieves certain results in optimization theory, but the optimization results are not obvious in terms of actual feedback [19–21]. The main reason for this is that overall system optimization is reduced and the influence and constraints of site selection on the path are not considered. Therefore, in this paper, in order to achieve a quantifiable representation of the optimization effect, an optimization model for the agricultural production waste recycling network siting-path problem is constructed with the optimization objective of minimizing the overall recycling network operational and construction costs, which specifically include the facility construction cost, the vehicle transportation cost, and others. Moreover, we aimed to optimize the siting of agricultural production waste collection points. A genetic algorithm was used to establish the location of the agricultural waste collection point and the route planning of the recycling and transportation vehicles [22–24].

3. Agricultural Production Waste Recycling Network Site Selection–Path Optimization Model Construction

3.1. Model Assumptions

LRP belongs to an NP-hard problem containing two sub-problems: the LAP facility siting problem and the VRP path optimization problem. In solving the LRP problem, the exact solution results often cannot be directly derived, so it is necessary to make assumptions on certain conditions and environments of the constructed model in order to improve the feasibility and practicality of the model, which is convenient to solve and highly adaptable. For the corresponding algorithm and the actual situation, this paper makes the following assumptions concerning the model:

![Diagram of agricultural production waste recycling and transfer.](image)
(1) Agricultural production waste generated at the point of generation comprises the same type of items, i.e., agricultural production waste in the broad sense, and the same type of transportation vehicles are used to carry out the recycling work;

(2) The agricultural waste recycling network in this paper is divided into three levels, the final number of agricultural production waste treatment points is one, and the number of agricultural production waste collection points is determined. Agricultural production waste can only be transported from the generation point to the collection point and then to the treatment point, i.e., it cannot be transported directly from the generation point to the treatment point;

(3) Only one vehicle is available for each driving path, i.e., from the agricultural production waste collection point to the generation point. Vehicles start from the collection point and go to the waste generation point on the planned route for collection and transportation in turn. Only one transportation vehicle works for each collection point, and the vehicle returns to the waste collection point after completing collection and transportation;

(4) Each transportation vehicle serves more than one waste generation point, and each vehicle only undertakes one transport collection activity;

(5) Through data collection and analysis, the amount of agricultural production waste generated at each generation point is determined, and the total amount of waste on the service route is less than the loading capacity of the transportation vehicle;

(6) According to the characteristics of a small volume and wide distribution of agricultural production waste, it is assumed that each waste generation point has a fixed generation time in the transportation and recycling cycle, and the generation volume of each generation point is independent and does not affect any other;

(7) It is assumed that each agricultural production waste collection point and treatment point has the same recycling and treatment capacity, and the annual working time is determined to be the same for each;

(8) The transportation cost per unit distance is known and the same, and the cost was calculated to include the vehicle transportation cost, the depreciation cost, and the labor cost;

(9) The working conditions of agricultural production waste collection points and treatment points are stable, and accidents such as transport vehicle breakdown and road blockage are excluded.

3.2. Variables and Symbols Description

| G  | denotes the set of potential agricultural production waste collection points \( G = \{ r | r = 1, 2, \ldots, R \} \); |
|---|---|
| H  | denotes the set of all agricultural production waste generation points \( H = \{ i | i = R + 1, R + 2, \ldots, R + N \} \); |
| S  | denotes the sum of potential agricultural production waste collection and generation points \( S = G \cup H \); |
| V  | denotes the set of \( K \) transport vehicles that can reach the collection point path \( V = \{ v_k | k = 1, 2, \ldots, K \} \); |
| F  | denotes the fixed cost of establishing an agricultural production waste collection point at \( r (r \in G) \); |
| \( C_{ij} \) | denotes the transportation cost per unit distance from service point \( i \) to service point \( j \) (including to the agricultural production waste collection point) \( (i, j \in S) \); |
| \( d_{ij} \) | denotes the distance from service point \( i \) to service point \( j \) (including to the agricultural production waste collection point) \( (i, j \in S) \); |
| \( q_j \) | denotes the amount of waste generated at service point \( j \); |
| \( Q_k \) | indicates the loading capacity of the transport vehicle \( K \); |
| \( W_r \) | denotes the average operating cost of the agricultural production waste collection point established at \( r \); |
Decision variables:

\[
X_{ijk} = \begin{cases} 
1, & \text{kth transport vehicle from service point i to service point j (including to the collection point)} \in S, k = 1, 2, \ldots, k, i \neq j \\
0, & \text{Otherwise}
\end{cases}
\]

\[
Z_r = \begin{cases} 
1, & \text{Create collection point at alternative address r, r \in G} \\
0, & \text{Otherwise}
\end{cases}
\]

3.3. LRP Model Construction for Agricultural Production Waste Recycling

Objective function:

\[
\text{Min} F = \sum_{i \in S} \sum_{j \in S} \sum_{k \in V} C_{ij} X_{ijk} d_{ij} + \sum_{r \in G} (F_r + W_r) Z_r
\]  

Binding conditions:

\[
\sum_{k \in V} \sum_{i \in S} X_{ijk} = 1, \forall j \in H
\]

\[
\sum_{j \in S} q_j \sum_{i \in S} X_{ijk} \leq Q_k, \forall k \in V
\]

\[
\sum_{i \in S} X_{ipk} - \sum_{i \in S} X_{pjk} \geq 0, \forall k \in V, p \in S
\]

\[
\sum_{r \in G} \sum_{j \in H} X_{rjk} \leq 1, \forall k \in V
\]

\[
\sum_{i \in S} X_{ipk} - \sum_{i \in S} X_{pjk} \geq 0, \forall r \in G
\]

\[
\sum_{r \in G} \sum_{i \in S} X_{rjk} - Z_r \leq 0, \forall k \in V, r \in G
\]

\[
\sum_{r \in G} \sum_{i \in S} X_{rjk} + \sum_{j \in H} \sum_{m \in G} X_{jmk} \leq 1, \forall k \in V
\]

\[
X_{ijk} = 0 \text{ or } 1, \forall i, j \in S, k \in V
\]

\[
Z_r = 0 \text{ or } 1, \forall r \in G
\]

Objective function (1) represents the minimal total cost of the agricultural waste recycling system, the first term of which is the transportation cost and the second term is the construction and operational cost of the agricultural waste collection point; constraint (2) restricts each waste generation point to be served by only one transportation vehicle; constraint (3) indicates that the sum of waste on each recycling transportation route does not exceed constraint (4), which ensures the spatial continuity of the recycling route; constraint (5) indicates that each recycling route starts from at most one agricultural waste collection point; constraint (6) indicates that there is no connection between agricultural waste collection points; constraint (7) ensures that the recycling route of each transport vehicle starts from constraint (7), which ensures that the starting point of the recycling transport route of each transport vehicle is an agricultural production waste collection point; constraint (8) ensures that the recycling transport route of each transport vehicle can only have one agricultural production waste collection point as the starting point; constraint (9) ensures that any two agricultural production waste collection points are not on the same recycling transport route; constraint (10) and constraint (11) ensure that the integer constraints are satisfied [25].

4. Discussion

4.1. Algorithm Description

In order to solve the NP-hard problem of LRP, the heuristic algorithm has the advantage of finding the global optimal solution, and the final optimization purpose of this paper is to consider the LAP and VRP problems as a unified whole to achieve the minimum operating cost of agricultural production waste recycling network, plus the genetic
algorithm has the characteristics of searching the global optimum, not easy to fall into the optimal solution and strong generalization ability [26], so this paper uses genetic algorithm combining with the optimization model of agricultural production waste recycling network to carry out the process design work of algorithm solving.

In order to ensure the accuracy of the solution and to design the genetic algorithm steps specifically for the optimization model in this paper, there are three main issues.

1. For the encoding of the feasible solution of the model, i.e., how to represent the feasible solution of the model in the form of real number genetic encoding.
2. Establishing an expression for the fitness function that is feasible and accurately describes the relationship between the individuals of the population and the problem constraints.
3. Determining the genetic mechanisms such as replication, crossover, and mutation in the genetic algorithm process and the stopping conditions of the algorithm [27–30].

4.2. Chromosome Encoding

After studying the structure of the solution to the site-path problem, it became clear that the feasible solution requirements for the optimization of the LRP problem of the agricultural production waste recycling network in this paper should accurately express the logistics information from three perspectives: recycling network facility siting, transport vehicle task assignment, and transport vehicle path planning. This is because, according to the requirements of the genetic algorithm solution, the solution information of the feasible solution set cannot be directly involved in the operation. When the genetic operation is performed, what is involved in the solution is the chromosome coding string corresponding to the solution set, so when designing the chromosome coding form, it is necessary to consider the accurate expression of the three aspects of the LRP problem solution. Furthermore, it is possible to put specific constraints on the feasible solution, and finish the solution after the population evolution is completed by accurately carrying the solution information.

In the solving process, the chromosomal coding string carrying the optimal solution information is used to solve the problem. Therefore, the real number coding method based on the numerical permutation of agricultural production waste generation and collection points was selected for the optimization model constructed in this paper. Firstly, the waste generation points and collection points are numbered and encoded using the serial numbers of each service point. Supposing there are n agricultural production waste treatment points and m agricultural production waste generation points, then each chromosome length is $m + n$ but must contain all non-repeating waste generation point serial numbers. Therefore, the serial numbers of agricultural production waste treatment points can be repeated and split into several sub-strings by the serial numbers belonging to waste collection points, and each sub-string contains treatment point serial numbers, collection point serial numbers, and the collection point arrangement order. In addition, each sub-string contains the processing point serial number, the collection point serial number, and the collection point arrangement order, and the processing point serial number is at the starting position of each sub-string. Thereafter, the serial number belonging to the production point represents the sequence of recycling transport vehicles visiting the production point, each sub-string represents a transport vehicle recycling path, i.e., the recycling transport vehicles start from the collection point, carry out recycling transport according to a certain driving path, and finally return to the collection point.

Suppose there are four alternative agricultural production waste collection points and eight agricultural production waste generation points, i.e., 1, 2, 3, and 4 denote the waste collection point serial numbers, and 5, 6, 7, 8, 9, 10, 11, and 12 denote the waste generation point serial numbers. For example, a certain chromosome $V_k = \{2, 8, 10, 11, 3, 7, 6, 12, 1, 1, 9, 5\}$ contains three sub-strings, namely, $\{2, 8, 10, 11\}$, $\{3, 7, 6, 12\}$, and $\{1, 1, 9, 5\}$. The first sub-string $\{2, 8, 10, 11\}$ indicates the travel route $2 \rightarrow 8 \rightarrow 10 \rightarrow 11 \rightarrow 2$; the agricultural production waste disposal point 4 does not appear in the chromosome, while the agricultural production waste disposal point 1 is repeated, so the chromosome code may take the three forms shown in Table 1 [31–33].
In form (I), chromosome \([2 8 10 11 3 7 6 12 1 9 5]\) contains three sub-strings, the first sub-string \([2 8 10 11]\) indicates that agricultural production waste collection point 2 is responsible for waste collection at waste generation points 8, 10, 11; the second sub-string \([3 7 6 12]\) indicates that agricultural production waste collection point 3 is responsible for waste collection at waste generation points 7, 6, 12; in the third sub-string \([1 1 9 5]\), waste collection point 1 appears twice, so the second gene 1 is deleted and the variant becomes sub-string \([1 9 5]\), which indicates that waste collection point 1 is responsible for waste collection at waste generation points 9, 5; and waste collection point 4 is not enabled.

In form (II), chromosome \([3 1 7 9 10 11 12 2 3 6 5 8]\) contains two sub-strings. The first sub-string \([3 1 7 9 10 11 12]\) appears with agricultural production waste collection points 3 and 1, so collection point 1 is removed and collection point 3 is retained, and the variant becomes \([3 7 9 10 11 12]\), which indicates that waste collection point 3 is responsible for waste collection at waste generation points 7, 9, 10, 11, 12. Similarly, the second sub-string \([2 3 6 5 8]\) becomes \([2 6 5 8]\), which means that waste collection point 2 is responsible for waste collection at waste generation points 6, 5, and 8.

In form (III), the chromosome \([3 1 7 9 10 11 12 3 2 6 5 8]\) contains two sub-strings. The first sub-string by variation becomes \([3 7 9 10 11 12]\) and the second sub-string by variation becomes \([3 6 5 8]\), i.e., the first sub-string and the second sub-string indicate that waste collection point 3 is responsible for the waste collection at waste generation points 5, 6, 7, 8, 9, 10, 11, 12, and form two routes from collection point 3.

4.3. Initializing the Population

According to the real number coding based on the combination of number permutations of agricultural production waste generation and collection points used in this paper, a feasible solution was obtained, in which a chromosome is a random series of length \(m + n\) from 1 to \(m + n\), and the first place of the series must be randomly generated by the serial number of agricultural production waste collection points. The final initialized population is a random series of real numbers that generates a population size \(S\) group.

4.4. Determining the Fitness Function

In genetic algorithms, the concept of fitness is generally used to measure the degree to which each chromosome in the population is chromosomally close to the optimal solution in each generation of the optimization calculation, and the individual fitness value is related to the value of the objective function of the problem and determines whether the chromosome is retained or not. In this paper, the fitness function value is a very large indicator and the objective function value is a very small indicator when solving, so, in order to ensure that the fitness function value is between \([0, 1]\) and is a very large indicator, we determined the fitness function as follows:

\[
f(x) = \frac{1}{\sum_{i \in S} \sum_{j \in S} \sum_{k \in V} C_{ij}X_{ij}q_{ij}d_{ij} + \sum_{r \in G}(F_r + W_r)Z_r}
\]  

4.5. Determining the Selection Mechanism

In this study, we chose the roulette wheel selection method. When using this method, the probability of each individual being selected is proportional to its fitness value, and the probability of being selected is determined according to the size of the fitness. The main steps are as follows:
1. Calculate the sum of fitness values for each generation of the population:

\[ F = \sum_{k=1}^{\text{pop.size}} f_k \]  

(13)

2. Calculate the probability of each chromosome being copied, i.e., the selection probability \( P_k \):

\[ P_k = \frac{f_k}{F}, \quad k = 1, 2, 3, 4 \ldots, m \]  

(14)

3. Calculate the cumulative probability of each chromosome being copied \( Q_k \):

\[ Q_k = \sum_{i=1}^{k} P_k \]  

(15)

4. Generate a random number \( N \) uniformly distributed between \([0, 1]\) equal to the number of population sizes;

5. If \( Q_{k-1} \leq N \leq Q_k \), chromosome \( V_k \) is selected.

### 4.6. Crossover Operation

In this study, the crossover operation, using the method of partially matched crossover for crossover work, first selects two parental chromosomes according to the crossover probability \( P_c \) in the genetic parameters, and then generates random number fragments of equal length in the two parental chromosomes and swaps them. The specific steps of chromosome crossover are as follows.

1. Select the parameter \( P_c \) as the probability of the crossover operation to generate a uniformly distributed pseudo-random number \( r_k (k = 1, 2, 3 \ldots m) \) between \([0, 1]\), select \( V_k \) as a parent if \( r_k < P_c \), and then randomly pair \((V_i, V_j)\) for the selected parent, where \((1 \leq i < j \leq m)\).

2. The randomly selected equal-length chromosome segments \( C_i \) and \( C_j \) in parents \( V_i \) and \( V_j \) are crossed over each other. Firstly, \( C_i \) in \( V_i \) is moved to the end of \( V_j \) and \( C_j \) in \( V_j \) is moved to the end of \( V_i \) using the position swap operation; secondly, the duplicate segments in \( V_j \) and \( C_i \) and \( V_i \) and \( C_j \) are deleted, respectively, to obtain the offspring chromosomes of \( V_i \) and \( V_j \), respectively, (see Table 2).

### 4.7. Mutation Operation

The mutation operation in this paper selects chromosomes for mutation based on the mutation probability \( P_m \), and takes the form of single or multiple gene substitutions in a single chromosome.

For a single gene variation of a single chromosome, two random gene positions in the chromosome are swapped to complete the mutation operation. For a multi-gene variation of a single chromosome, two chromosome segments of lengths less than \((m + n)/2\) are swapped to complete the mutation operation. Table 3 shows the example above for illustrative purposes.
Table 3. The above example illustrates chromosomal gene conversion.

<table>
<thead>
<tr>
<th>Pre-mutation chromosomes</th>
<th>Single Gene Variants</th>
<th>Multi-Gene Variants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromosomes after mutation</td>
<td>2 8 1 1 3 7 6 12 1 9 5</td>
<td>2 8 1 1 3 7 6 12 1 9 5</td>
</tr>
</tbody>
</table>

4.8. Stopping Operation of the Genetic Algorithm

The stopping condition of the genetic algorithm in this paper is when the number of breeding generations reaches the set maximum number of generations, i.e., the genetic cycle operation can be stopped, and the maximum number of evolutionary generations is used to limit the number of times the algorithm is executed. However, in order to prevent the occurrence of an error code, after the algorithm stops, it is necessary to judge the first gene position of each chromosome in the population. When the first gene position is the agricultural production waste collection point serial number, the algorithm can be solved. When the first gene position is not the agricultural production waste collection point serial number, it is necessary to generate a random agricultural production waste collection point serial number before the first gene position (see Table 4).

Table 4. Example of stop operation of the genetic algorithm.

<table>
<thead>
<tr>
<th>Chromosomes after cycle arrest</th>
<th>Occurrence of the First Bit of Non-Agricultural Production Waste Collection Point Serial Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Randomly generated waste collection point serial number</td>
<td>8 1 1 7 1 1 9 5 1 2 2 3 6</td>
</tr>
</tbody>
</table>

4.9. Algorithm Steps

Through the design of the basic steps in the above genetic algorithm, the optimal genetic algorithm for solving the agricultural production waste recycling network in this paper is summarized as follows:

Step 1: coding operation of the service points of the agricultural production waste recycling network;
Step 2: initialization of the algorithm and setting the relevant parameters. The termination criterion for evolutionary generation $T$ in this paper was 300, the crossover probability $P_c$ was 0.7, and the variation probability $P_m$ was 0.005;
Step 3: randomly generate the initial population $POP(0)$;
Step 4: the population starts to evolve and the fitness function value of each chromosome in the population is calculated and replicated to the next generation population $POP(N + 1)$ according to the roulette wheel selection method;
Step 5: crossover and mutation operations are performed on $POP(N + 1)$;
Step 6: If the termination condition is satisfied, perform the judgment operation, otherwise, return to step 4 to continue the evolution.

5. Example Verification and Result Analysis

5.1. Description of the Algorithm

The generation of agricultural production waste has the characteristics of uncertainty, a wide distribution, and small individual production overall. As one agricultural production waste collection point may not be able to meet the recycling and transportation treatment needs of all agricultural production waste generation points, it is necessary to adopt a multi-facility siting strategy for agricultural production waste collection points. For the three-level agricultural production waste recycling network model in this paper, agricultural waste from agricultural production waste generation points is transported by transportation vehicles to the corresponding agricultural production waste collection points; however, the generation volume of each generation point is small and the geographical distribution of generation points is extensive, so effective planning arrangements for the transportation routes of multiple transportation vehicles are required. In addition, in order
to verify the effectiveness and practicality of the site-path problem optimization model of the agricultural production waste recycling network in this paper, the data related to 21 agricultural production waste generation points and four agricultural production waste collection points were selected using numerical simulations. The Matlab R2016a software was used for the site-path problem optimization model. The path problem optimization model was programmed and the relevant coordinates and yield data of agricultural production waste generation and collection points are shown in Tables 5 and 6. The relative location representation is shown in Figure 4.

Table 5. Coordinates of agricultural production waste recycling network facilities.

<table>
<thead>
<tr>
<th>X Coordinate</th>
<th>Y Coordinate</th>
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<td>73.7465</td>
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<td>23</td>
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<tr>
<td>24</td>
<td>99.8923</td>
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<tr>
<td>25</td>
<td>73.0712</td>
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</table>

Table 6. Agricultural production waste generation point generation statistics.

<table>
<thead>
<tr>
<th>Point of Generation</th>
<th>Generation (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>250.31</td>
</tr>
<tr>
<td>6</td>
<td>210.22</td>
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<tr>
<td>7</td>
<td>220.11</td>
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<tr>
<td>8</td>
<td>230.29</td>
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<tr>
<td>9</td>
<td>250.31</td>
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<tr>
<td>10</td>
<td>220.42</td>
</tr>
<tr>
<td>11</td>
<td>250.5</td>
</tr>
<tr>
<td>12</td>
<td>210.08</td>
</tr>
<tr>
<td>13</td>
<td>240.26</td>
</tr>
<tr>
<td>14</td>
<td>230.8</td>
</tr>
<tr>
<td>15</td>
<td>230.02</td>
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<td>240.92</td>
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<td>17</td>
<td>230.73</td>
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<tr>
<td>18</td>
<td>210.48</td>
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<tr>
<td>19</td>
<td>200.57</td>
</tr>
<tr>
<td>20</td>
<td>250.23</td>
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<tr>
<td>21</td>
<td>210.45</td>
</tr>
<tr>
<td>22</td>
<td>200.96</td>
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<td>23</td>
<td>230.54</td>
</tr>
<tr>
<td>24</td>
<td>250.52</td>
</tr>
<tr>
<td>25</td>
<td>240.23</td>
</tr>
</tbody>
</table>
5.2. Related Parameter Settings

In this paper, the four agricultural production waste collection points are numbered in order in natural numbers from 1 to 4, and the 21 agricultural production waste generation points are numbered in order in natural numbers from 5 to 25. The unit transportation cost $C_{ij} = 1.05 \text{CNY/km·kg}$, the construction and operational costs of agricultural production waste collection points $W_r + F_r$, the specific construction and operational costs, including manager and staff salaries, equipment maintenance, daily necessary expenses of collection points, equipment expenditure, fixed equipment cost, etc., are shown in Table 7.

Table 7. Construction and operational costs of agricultural production waste collection points.

<table>
<thead>
<tr>
<th>Agricultural Production Waste Collection Point Number</th>
<th>Chromosome Code Sequence Number</th>
<th>Construction and Operation Cost (Wr + Fr)/CNY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>180,000</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>210,000</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>151,000</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>163,000</td>
</tr>
</tbody>
</table>

The parameters of the genetic algorithm were set as follows: the termination criterion for evolutionary generation $T$ was 400, the crossover probability $P_c$ was 0.7, and the variation probability $P_m$ was 0.005.

In this study, we chose to use the straight-line distance formula to represent the distance between two service points in the example. Furthermore, considering that in reality, the straight-line distance has a certain deviation from the real distance, we needed to add the detour coefficient $W_{ij}$ in front of the straight-line distance to represent the actual traffic condition. Referring to the relevant information, the detour coefficient $W_{ij} = 1.5$ in rural areas, and the distance formula (16) between two points in this paper is as follows:

$$d_{ij} = w_{ij} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$  \hspace{1cm} (16)

5.3. Optimization Scheme Based on Genetic Algorithm Solution

For the purpose of agricultural production waste recycling network optimization, matlab software was able to derive the optimization results after 210 s. The optimization results after completing the parameter settings are shown in Figure 5.
As can be seen in Table 8, the agricultural production waste recycling network LRP problem combined with the genetic algorithm optimization results enabled all four agricultural production waste recycling points to operate at a total construction and operational cost of CNY 1,720,801,000. The total cost of the single recycling route was CNY 457,892. Recycling transport route 1 ran from collection point 1 to agricultural production waste generation points 20, 11, 24, 18, and 15 and back to collection point 1. Recycling transport route 2 ran from collection point 2 to agricultural production waste generation points 22, 6, 13, 21, 23, and 25. The total cost of the single recycling route was CNY 553,594. The third recycling route ran to agricultural production waste generation points 19, 8, 12, and 7 and returned to collection point 3, with a total cost of CNY 15,698. The fourth recycling route ran to agricultural production waste generation points 5, 14, 9, 16, 17, and 10 and returned to collection point 4, with a total cost of CNY 315,698. Finally, recycling transport route 5 ran to agricultural production waste generation points 17 and 10 and returned to collection point 4, with a total cost of CNY 394,897.

Table 8. Optimization scheme.

<table>
<thead>
<tr>
<th>Agricultural Production Waste Recycling Station Number</th>
<th>Recovery of Transport Vehicle Paths</th>
<th>Total Cost of a Single Recovery Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-20-11-24-18-15-1</td>
<td>457,892</td>
</tr>
<tr>
<td>2</td>
<td>2-22-6-13-21-23-25-2</td>
<td>553,594</td>
</tr>
<tr>
<td>3</td>
<td>3-19-8-12-7-3</td>
<td>315,698</td>
</tr>
<tr>
<td>4</td>
<td>4-5-14-9-16-17-10-4</td>
<td>394,897</td>
</tr>
<tr>
<td><strong>Total Program Cost</strong></td>
<td></td>
<td><strong>1,722,081</strong></td>
</tr>
</tbody>
</table>

For the selection of agricultural production waste treatment points, the cost of new treatment points was much higher than the cost of renovating collection points. Considering the optimization goal of minimizing the system operational cost and the difference in the cost of selecting sites for the four alternative agricultural production waste collection points, the agricultural production waste collection point 4, with the lowest construction and operational cost, was selected as the agricultural production waste treatment point.

According to the operational results, on the basis of solving the problem with the genetic algorithm, the time used, i.e., 210s, was much less than that of the traditional
exact algorithm. Moreover, if the scale of the system is expanded, the traditional exact algorithm will become extremely inefficient. As shown in Figure 6, according to the relationship graph between the objective function and the number of genetic generations, the population starts to converge at 320 generations, which also proves the feasibility and effectiveness of the genetic algorithm in terms of solving the optimized LRP model of the agricultural production waste recycling network.

Figure 6. Plot of adaptation function versus genetic generation.

6. Conclusions

In terms of turning waste into an asset and enhancing the added value of the agricultural industry, agricultural waste resource utilization has broad prospects. The collection and transportation of agricultural production waste should be the key object of research to achieve the efficient and environmentally friendly operation of the agricultural production waste recycling network. Focusing on agricultural production waste, which is huge in quantity, diverse in type, widely distributed and scattered, with a small amount of waste generated in each place, this paper establishes an optimization model for the agricultural production waste recycling network LRP problem based on a genetic algorithm solution. Moreover, we conducted research and optimization on the site selection of agricultural production waste collection points and the planning of agricultural production waste recycling vehicle transportation routes.

(1) In this paper, the research focus was determined from the two perspectives of agricultural production waste facility site selection and transportation vehicle path optimization, in which the LRP problem brings together the LAP problem and the VRP problem. Studies into the LAP problem ignore the route arrangement problem, and the VRP problem is based on the premise that the locations and numbers of each facility and the customer are known, and the transportation vehicle path is reasonably arranged. To find a solution to the LAP problem and the VRP problem, a two-stage solution is required, resulting in inconsistencies. Thus, this paper adopted the LRP problem model for facility site selection and the transportation route arrangement to ensure the consistency of the final optimization results;

(2) This paper constructs an optimization model for the agricultural production waste recycling network based on the LRP problem. We took the minimization of network operational costs as the optimization objective, we obtained basic data of 21 agricultural production waste and 4 potential agricultural production waste collection points through a numerical simulation, we took these 25 agricultural production waste
facility points as the research object, and finally, we considered the whole recycling network using the three indicators of greenness. The genetic algorithm was chosen to solve the overall optimization scheme;

(3) In this study, the genetic algorithm was selected to solve the optimization model of the agricultural production waste recycling network based on the LRP problem, and the decimal natural number coding form was adopted for the facility points in the network. The purpose was to improve the convergence speed and avoid falling into local optimum. Finally, the exact location of the agricultural production waste facilities and the corresponding waste recycling vehicle transportation routes were obtained using the Matlab software.

Green and clean agriculture depend on development and ecology. Vigorously promoting the deep integration of rural industries at all levels helps accelerate the transformation of agriculture, thus increasing the efficiency of capital and accelerating the comprehensive utilization of agricultural waste resources. Multiple measures should be taken to comprehensively promote the green development of agriculture. The research in this paper can be used to establish an efficient, economic, and environmentally friendly agricultural production waste recycling network, forming a complete ecological recycling industry chain. Moreover, it can be used to reduce agricultural waste pollution, promote ecological recycling in the farming and breeding industries, and is of great significance to the construction of reverse logistics in rural areas.

Author Contributions: Conceptualization, X.W. and W.N.; methodology, X.W.; software, X.W.; validation, W.N. and D.Y.; formal analysis, X.W. and W.N.; investigation, D.Y.; resources, X.W.; data curation, X.W.; writing—original draft preparation, X.W.; writing—review and editing, K.W.; visualization, D.Y. and K.W.; project administration, X.W. and W.N. All authors have read and agreed to the published version of the manuscript.

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References

5. Yang, L.L.; Xiao, X.; Gu, K. Agricultural waste recycling optimization of family farms based on environmental management accounting in rural China. Sustainability 2021, 13, 5515. [CrossRef]


13. Antic, I.; Skrbic, B.D.; Matamoros, V.; Bayona, J.M. Does the application of human waste as a fertilization material in agricultural production pose adverse effects on human health attributable to contaminants of emerging concern? *Environ. Res.* 2020, 182, 109132. [CrossRef]


27. Guo, P.; Wang, X.; Han, Y. The enhanced genetic algorithms for the optimization design. In Proceedings of the 3rd International Conference on Biomedical Engineering and Informatics (BMEI 2010), Yantai, China, 16–18 October 2010. [CrossRef]


