

# Optimization of Crop Planting Strategy Based on Mixed-Integer Programming under Multiple Scenarios

Shiya Du\*

Trier College of Sustainable Technology, Yantai University, Yantai, China, 11066

\*Corresponding author: ISANDYU@outlook.com

**Abstract.** Agriculture serves as the bedrock of the rural economy, directly determining household incomes and food security while providing essential support for extending industrial chains and fostering related industries. Selecting suitable crops requires 2 with regional climate and soil conditions, while rational planting strategies must balance profitability with ecological considerations—both being crucial for achieving sustainable rural development. This study examines a village with diverse farmland types—flat dryland, terraced fields, slopes, irrigated land, and both standard and smart greenhouses. By optimizing annual crop selections across these terrains and applying mixed-integer programming (MIP) to planting strategies, it tracks yield fluctuations under varying approaches. This methodology proves effective in minimizing resource wastage, boosting profitability, and mitigating market volatility. The results indicate that by fully considering the specific demand trends for different crop categories over the years, the real-time fluctuation patterns of market vegetable prices during different seasons and holidays, as well as the substitutability in planting space and growth cycles and the ecological complementarity among various crops, the resulting planting strategy can effectively reduce waste of resources such as land, water, fertilizers, and labor. It significantly increases farmers' planting income, providing a solid and practical scientific basis for steadily increasing crop yields, sustained growth in agricultural economic benefits, and the sustainable development goal of balancing rural ecological conservation with economic growth.

**Keywords:** Crop Planting Strategy, Arable Land Resource Optimization, Substitutability and Complementarity, Mixed-Integer Planning, MIP.

## 1. Introduction

Agriculture is the foundation of rural economy [1], and the selection of appropriate crops and reasonable planting strategies is crucial to the sustainable development of rural areas [2]. In different types of arable land due to different characteristics of different types of crop planting efficiency yield is different, through mathematical modeling analysis of crop sales and analysis of the correlation and substitutability to optimize crop planting strategy, can effectively reduce the waste of resources and to cope with market fluctuations, improve the production efficiency and market earnings [3] [4]. This study aims to optimize the crop planting scheme in this village through mixed integer programming by using the past data of a certain region in order to improve the economic efficiency of the village.

Given the increasingly scarce land resources and the distinct limitations of different farmlands in terms of soil fertility [5], irrigation conditions, and climate adaptability, selecting ecologically compatible crops tailored to regional natural endowments while optimizing planting schedules and crop combinations based on market demand and growth patterns not only streamlines field management and reduces maintenance costs but also tangibly enhances productivity per unit area. This approach effectively mitigates planting risks stemming from natural disasters, market fluctuations, and other uncertainties [6], providing robust safeguards for stable farmer income. This paper breaks down the ultimate objective into three progressively detailed research questions (RQs):

RQ 1: Ideally, regardless of planting risks and market changes, find the optimal planting solution for the region for the scenarios of “more than the saleable portion is wasted” and “more than the saleable portion is sold at 50% of the previous year's sales price” and “more than the saleable portion

is sold at 50% of the previous year's sales price". "Find the optimal planting plan for the area under the two scenarios.

RQ2: Based on the forecasted price (under the optimal scenario from either "waste from unsold surplus" or "selling surplus at 50% of historical prices"), determine the profit of the optimal planting scheme while accounting for uncertainties in expected sales volume, yield per mu, planting costs, sales prices, and potential planting risks across crops.

RQ3: Conduct a comprehensive analysis of the substitutability and complementarity among crops and factors, perform classification and regression, and determine the profit of the optimal planting scheme.

## 2. Mathematical solutions for crop planting strategies in ideal conditions

Ideally this paper use previous years' data to forecast expected sales volume. Find the optimal solution for two different scenarios without taking into account market uncertainties

### 2.1. Derivation of objective function graph

This paper take maximizing the actual profit as our planting objective. This paper split the real profit into two parts: total profit and overcapacity loss.

Regardless of stagnation and waste or selling at a reduced price, the profit formula for crop  $j$  on plot  $i$  in season  $s$  of year  $t$  is:

$$z_{ijts} = x_{ijts} \cdot B_{ijts} \cdot Y_{jt} - x_{ijts} \cdot C_{ijts} \quad (1)$$

Sum the individual profits to obtain the total profit formula:

$$Z_t = \sum_i \sum_j \sum_s z_{ijts} \quad (2)$$

For the case of "more than part of the stagnant sales, resulting in waste", the profit in excess of the expected sales volume should be deducted, and the formula for the loss of overcapacity is:

$$\sum_j \max \left( 0, \sum_i \sum_s x_{ijts} \cdot B_{ijts} - E_j \right) \cdot Y_{jt} \quad (3)$$

In the case of "selling the excess portion at a price reduction of 50% of the sales price in 2023", the profit on the excess expected sales volume shall be deducted by 50%, and the formula for the loss of overcapacity is as follows:

$$\frac{1}{2} \sum_j \max \left( 0, \sum_i \sum_s x_{ijts} \cdot B_{ijts} - E_j \right) \cdot Y_{jt} \quad (4)$$

To address the problem of "wasteful over-selling", this paper propose the following objective function:

$$\max P_t = \sum_i \sum_j \sum_s (x_{ijts} \cdot B_{ijts} \cdot Y_{jt} - x_{ijts} \cdot C_{ijts}) - \sum_j \max \left( 0, \sum_i \sum_s x_{ijts} \cdot B_{ijts} - E_j \right) \cdot Y_{jt} \quad (5)$$

For the problem of "selling the excess portion at 50% of the sales price in 2023", this paper propose the following objective function:

$$\max P_t = \sum_i \sum_j \sum_s (x_{ijts} \cdot B_{ijts} \cdot Y_{jt} - x_{ijts} \cdot C_{ijts}) - \frac{1}{2} \sum_j \max \left( 0, \sum_i \sum_s x_{ijts} \cdot B_{ijts} - E_j \right) \cdot Y_{jt} \quad (6)$$

where  $x_{ijts}$  denotes the area of crop  $j$  planted on plot name  $i$  in season  $s$  of year  $t$ , which is the decision variable of the objective function,  $E_j$  denotes the expected total production and expected sales volume of crop  $j$ ,  $C_{ijts}$  denotes the planting cost of crop  $j$  in season  $s$  of year  $t$ ,  $Y_{jt}$  denotes the sales price of crop  $j$  in year  $t$ , and  $P_t$  denotes the total profit of all crops on all plots of land in year  $t$ , which is the decision variable of the objective function.  $B_{ijts}$  denotes the acre yield of crop  $j$  on land  $i$  in season  $s$  of year  $t$ .

## 2.2. Establishment of constraints

This constraint restricts the acreage of crops on each plot  $i$  to be less than not more than the available acreage of the plot:

$$X_{its} = \sum_j x_{ijts} \quad (7)$$

$$X_{its} \leq A_i \quad (8)$$

This constraint limits the maximum number of three crops that can be cultivated on the same plot  $i$  in the same season of the same year:

$$m_{ijts} = \begin{cases} 1, & x_{ijts} > 0 \\ 0, & x_{ijts} = 0 \end{cases} \quad (9)$$

$$1 \leq \sum_j m_{ijts} \leq 3 \quad (10)$$

Different plots can only be cultivated with specific crops, when  $i, j, s$  satisfy one of the following six cases only allowed to plant, otherwise not allowed to plant:

$$\textcircled{1} i \in [1, 26], j \in [1, 15], s=1$$

$$\textcircled{2} i \in [27, 34], j=16, s=1$$

$$\textcircled{3} i \in [35, 50], j \in [17, 34], s=1$$

$$\textcircled{4} i \in [35, 50], j \in [38, 41], s=2$$

$$\textcircled{5} i \in [51, 54], j \in [17, 34], s=1$$

$$\textcircled{6} i \in [51, 54], j \in [17, 34], s=2$$

This constraint restricts that on a particular plot  $i$ , if crop  $j$  is planted in the  $s$ th season, then crop  $j$  is not allowed to be planted again in the  $s-1$ st season, which ensures that there is no re-cropping:

$$m_{ijts} + m_{ij(t-1)s} \leq 1 \quad (11)$$

$$m_{ijt1} + m_{ijt2} \leq 1 \quad (12)$$

This constraint restricts the planting of legume crop at least once in three years on plot  $i$ :

$$q_t = \begin{cases} 0, & x_{ijts}, j \notin \text{Legumes} \\ 1, & x_{ijts}, j \in \text{Legumes} \end{cases} \quad (13)$$

$$1 \leq q_t + q_{t-1} + q_{t-2} \leq 6 \quad (14)$$

### 2.3. Solving and analyzing the model

The above problem is a MIP problem, which is more difficult to solve directly using the solver due to the max function in the objective function, this paper introduce an auxiliary variable  $z$  and convert this max function into a constraint so that  $z$  is greater than or equal to the value in all the max functions, thus linearizing the problem. Next, this paper used the MATLAB solver to solve the model and came up with the following conclusions in two different cases:

In the case of over-selling and wastage

(I) In this case, the solution prioritizes crops with more stable yields and clearer market demand, such as wheat and corn. These crops are more predictable market sales, even if the future climate or market conditions change, its impact on the overall revenue is smaller, the program can effectively avoid the waste caused by excess production.

(II) Vegetable crops or other crops with large yield fluctuations are planted in smaller areas. The market demand for these crops fluctuates greatly, and once the production exceeds the market demand, it may not only cause difficulties in sales, but also make the problem of waste due to overproduction even more serious, and this program effectively reduces the risk of sales.

In the case of reduce the price of the excess by 50% of the sales price.

(I)The Final Plan still favors crops with higher yields and demand growth potential, such as wheat and corn. Since these crops not only show a stable growth trend in future market demand, but also have more controllable yields, even if the expected sales volume is exceeded in a given year, the excess can still be partially recovered by selling at a discounted price. Therefore, even if the excess output of these crops needs to be sold at a price reduction of 50% of the original price, the overall income is still improved, so the reasonableness of the planting program is high.

(II)Vegetable crops are widely grown in greenhouses. Vegetables are daily consumer goods, and even if there is a stagnation in the sale of certain crops, the sale of vegetables can still provide a reliable source of income for farmers[7]. In the program, farmers can enhance the production of vegetables through greenhouse technology and take full advantage of the trend of rising vegetable prices to reduce the negative impact of declining sales prices on total returns. At the same time, the reasonable allocation of greenhouse resources and the priority planting of vegetable varieties with higher market demand can maximize the overall income while maintaining the yield, and the planting program is reasonable and reliable.

### 3. Mathematical Solutions to Crop Planting Strategie

Due to climate change and market conditions and other factors, the expected sales yield growth rate, cost growth rate, mu yield growth rate and price growth rate are changing, in the problem of a model on the basis of the known data and the meaning of the topic, this paper propose a variable for the correction of the model. As shown in Figure 1 below.

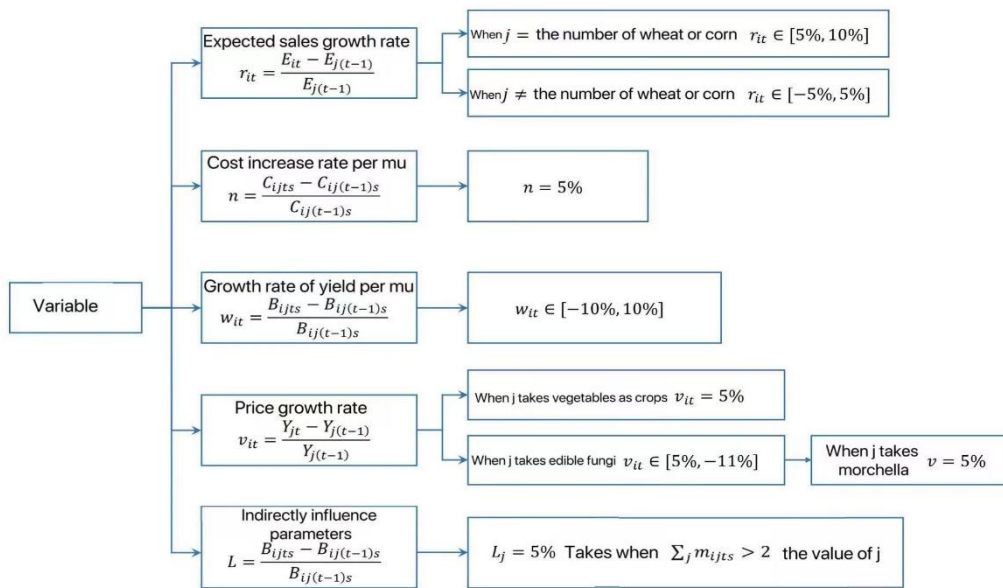


Figure 2 Analysis of the general idea of problem two

### 3.1. Parameter improvement

Due to the impact of climate change and market conditions and other factors, the expected sales yield growth rate, cost growth rate, mu yield growth rate and price growth rate are changing, on the basis of the model of Problem 1, according to the known data and the title of the information, this paper modify and improve the model of the covariates.

The expected crop sales volume growth rate  $r_{jt}$  formula is:

$$r_{jt} = \frac{E_{jt} - E_{j(t-1)}}{E_{j(t-1)}} \quad (15)$$

where  $E_{jt}$  and  $E_{j(t-1)}$  represent the expected sales volume of the current year and the expected sales volume of the previous year, respectively. According to the information in the title, the average annual growth rates of different crops will change in the corresponding intervals. The average annual growth rates of wheat and corn are between [5%,10%] and the rest of the crops are between [-5%,5%].

$$r_{jt} \in \begin{cases} [5\%,10\%], & j = 6, 7 \\ [-5\%, -5\%], & else \end{cases} \quad (16)$$

The formula for growth rate of crop yield per growth rate is  $\omega_{jt}$  is:

$$\omega_{jt} = \frac{B_{ijts} - B_{ij(t-1)s}}{B_{ij(t-1)s}} \quad (17)$$

where  $B_{ijts}$  and  $B_{ij(t-1)s}$  denote the current year's acre yield and the previous year's acre yield, respectively. According to the information in the question, there is a 10% fluctuation due to the interference of climatic and other real factors.

$$\omega_{jt} \in [-10\%,10\%] \quad (18)$$

The cost per growth rate  $n_{jt}$  formula is:

$$n_{jt} = \frac{C_{ijts} - C_{ij(t-1)s}}{C_{ij(t-1)s}} \quad (19)$$

where  $C_{jt}$  and  $C_{j(t-1)}$  denote the cost per acre of the current year and the cost per acre of the previous year, respectively. According to the information in the question, the cost growth is around 5%.

$$n_{jt} = 5\% \quad (20)$$

The formula for price growth rate of various crops  $u_{jt}$  is:

$$u_{jt} = \frac{Y_{jt} - Y_{j(t-1)}}{Y_{j(t-1)}} \quad (21)$$

where  $Y_{jt}$  and  $Y_{j(t-1)}$  denote the price of the current year and the previous year respectively. According to the information in the title, the selling price of food crops remains stable; the selling price of vegetable crops grows on average near 5% per year; the decrease in the selling price of edible mushrooms is located at [1%,5%], and the selling price of morel mushrooms decreases by 5%.

$$u_{jt} \in \begin{cases} \{0\}, j \in \{Grain\ products\} \\ \{5\%\}, j \in \{Vegetables\} \\ [-5\%, -1\%], j \in \{Edible\ types, excluding\ morel\ mushrooms\} \\ \{-5\%\}, j \in \{morel\ mushroom\} \end{cases} \quad (22)$$

### 3.2. Model Improvement

Then the model is improved as follows. This paper follow the planning model of RQ1, based on which the objective function and constraints are supplemented and amended:

Considering that “sell at a reduced price” is more in line with the real situation, the objective function adopts the situation of “sell at a reduced price of 50% of the previous year's sales price”. According to equations (15) (17) (19) (21), the expected growth rate of crop sales  $r_{jt}$ , crop yield per acre growth rate of  $\omega_{jt}$ , crop cost per acre growth rate of  $n_{jt}$ , the price growth rate of each type of crop  $u_{jt}$  will have a direct impact on the objective function of the expected sales  $E_{jt}$ , the cost of planting  $C_{jt}$ , acre yield  $B_{ijts}$ , the sales price of  $Y_{jt}$ .  $Y_{jt}$  have a direct impact. Therefore, this paper need to adjust these three parameters of the original objective function, and the adjustment result is expected sales volume  $E_{jt}^*$ , mu yield  $B_{ijts}^*$ , planting cost  $C_{jt}^*$ , and sales price  $Y_{jt}^*$ .

The modified objective function is:

$$\max P_t = \sum_i \sum_j \sum_s (x_{ijts} \cdot B_{ijts}^* \cdot Y_{jt}^* - x_{ijts} \cdot C_{ijts}^*) - \frac{1}{2} \sum_j \max \left( 0, \sum_i \sum_s x_{ijts} \cdot B_{ijts}^* - E_j^* \right) \cdot Y_{jt} \quad (23)$$

The expected sales volume, mu yield, planting cost and selling price have uncertainty. According to equation (16) (20) this paper know that some of the parameters fluctuate within the interval. This paper assume that these parameters obey a uniform distribution within the interval, and numerically

simulate the real-life uncertainty by taking random numbers through MATLAB[8], while ensuring that the parameters are constant, which facilitates the planning model analysis and solution.

Too many crop types in intercropping of food crops can easily increase the difficulty of management and cause yield reduction. Considering the potential planting risk, Eq. (8) in the constraints of Problem 1 is amended: for each additional crop in the plot, the mu yield decreases by 5% each time, which can be approximated as a 5% decrease in the upper limit of the planting area of the plot.

$$X_{its} \leq \left[ 1 - 5\% \left( \sum_j m_{jts} - 1 \right) \right] A_i \quad (24)$$

### 3.3. Model Solution and Analysis

The above problem is still a MIP problem, compared with the RQ1, this paper need to amend the parameters of the objective function, some modifications to the constraints, the rest of the solution method with the first question. The rest of the solution method is the same as the first problem.

This paper compare and analyze the results of the second question with the first question and get the following conclusions:

(I) The area planted to wheat and maize has been further increased in RQ2, as their demand will continue to grow in the coming years according to the market pattern, and planting these crops can better meet the market demand and enhance the total return.

(II) For other crops with highly fluctuating sales volumes, such as vegetables and pulses, acreage adjustments are more flexible than in RQ1, which ensures that yields can adapt to fluctuations in market demand and avoids overproduction or underproduction.

(III) For vegetable crops with an upward price trend, the program increased their planting area to capture the benefits of future price increases. For edible mushrooms with declining prices, especially morel mushrooms, the optimization scenario reduces their planting area to avoid the reduction in revenue from falling prices.

## 4. Research on crop relevance and substitutability

According to the definition of microeconomics, when there is a high degree of substitutability between crops, a decrease in the sales volume of one crop increases the sales volume of another crop. The substitutability of different crops can be explained by similarity, through the problem two model to get the known data, the establishment of hierarchical clustering model, the same kind of crop commonality is strong similarity is high, can be regarded as mutual substitution. Conversely, different classes can be regarded as complementary.

According to the data of expected sales volume, sales price, and planting cost used in building the model in Problem 2, this paper use Pearson's correlation coefficient to explore it, build the coefficient matrix and analyze it.

### 4.1. Clustering of different crops by hierarchical clustering method

Hierarchical clustering method[9] is an unsupervised learning algorithm based on data similarity and is widely used to explore hierarchical structures in data. The method describes the relationship between data by constructing a tree-like structure that shows how data are gradually aggregated or separated. The core idea of the hierarchical clustering method lies in gradually merging or splitting data points by calculating the similarity or distance between them, and eventually forming a clustering tree, also known as a dendrogram, which is able to intuitively reflect the hierarchical clustering results of the data.

This paper used spsspro, and through the hierarchical clustering method, this paper divided the crops into 3 categories, namely (1) hot crops; (2) flat crops; (3) slow-selling crops.

For crops in the same category, this paper consider them to be highly substitutable, which is due to their high similarity in terms of market demand, cultivation conditions and yield. For example, hot crops usually have strong market demand and high profit margins, have shorter growing cycles and are easily favored by consumers, so these crops can be substituted for each other to meet market demand. Flat-selling crops, on the other hand, tend to have stable demand and low price fluctuations, and are not prone to short-term imbalances between supply and demand. The substitutability of these crops is demonstrated by the fact that producers can choose among them according to market prices and planting conditions, in order to maintain a stable income. Producers can switch between lagging crops to minimize inventory buildup and losses due to lower market demand and chronically low prices.

For the different classes of crops, this paper believe that they are complementary due to the fact that they are able to complement each other in different time periods or market environments due to large differences in market demand and growing conditions. For example, hot crops usually have high market demand, but their production cycles may be concentrated in particular seasons or time periods. Flat and slow-moving crops, on the other hand, can fill market gaps and maintain a stable supply when demand for hot crops falls.

#### 4.2. Relationship between expected sales volume and sales price, planting costs

Based on the data obtained from RQ2, this paper use Spearman's correlation coefficient for discussion.

Spearman's correlation coefficient [10] is a nonparametric statistical method used to measure the monotonic relationship between variables. Unlike Pearson's correlation coefficient, Spearman's correlation coefficient does not require the data to obey a normal distribution and is suitable for analyzing variables with nonlinear relationships. The coefficient evaluates the correlation between two variables by calculating their ordinal relationship and is thus more robust to outliers and non-normally distributed data.

The Spearman's correlation coefficient is calculated through the following steps:

(I) Ordering the variables: the data of the two variables are sorted separately in ascending order, assigning an order to each data point.

(II) Calculate the order difference: for each corresponding data point, calculate the order difference between the two variables.

(III) Calculate the correlation coefficient: Based on the order difference, calculate the Spearman correlation coefficient using the following formula:

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \quad (25)$$

where  $d_i$  is the order difference of the  $i$ -th data point and  $n$  is the number of data points.

The objective of the model remains to maximize the economic returns of the villages, taking into account the substitutability and complementarity between crops. Based on the previous model, this paper further adjusted the following parameters:

(I) Expected sales volume and price: according to the results of correlation analysis, this paper adjusted the expected sales volume and sales price of each crop to make it more in line with the actual market situation.

(II) Planting area adjustment: By introducing substitutability and complementarity between crops, this paper adjusted the planting area of different crops. For crops with strong complementarity, the planting area is increased appropriately to ensure that the revenue is maximized in different periods of market demand.

This paper used SPSS pro and analyzed the expected sales volume, sales price and planting cost with Spearman's correlation coefficient matrix with the following results:

**Table 1** Spearman correlation coefficient matrix

	Expected sales volume	Sales price	Planting cost
Expected sales volume	1	0.73	-0.51
Sales price	0,73	1	-0.31
Planting cost	-0,51	-0.31	1

### 4.3. Conclusions

(I) Correlation between expected sales volume and sales price: the correlation coefficient is 0.73, indicating that there is a positive correlation between these two variables. Usually, the higher the selling price, the expected sales volume increases, which may be due to the fact that the higher-priced crops have better market demand and profit potential.

(II) Correlation between expected sales volume and planting cost: the correlation coefficient is -0.51, indicating that there is a negative correlation between expected sales volume and planting cost. The higher the planting cost, the lower the expected sales volume, probably because the market competitiveness of high-cost crops is weaker, which leads to a decline in sales volume.

(III) Correlation between sales price and planting cost: the correlation coefficient is -0.31, indicating a slight negative correlation between these two variables. Although the increase in cost does not significantly affect the sales price, it can be hypothesized that crops with high planting costs usually have lower prices, or it is difficult to reflect cost increases through prices.

The solution method is the same as the second question, and this paper compare the conclusion with RQ2 to get the following results:

(I) With the optimized planting strategy, the model of RQ3 performs better in coping with market fluctuations and resource allocation, and the total profit is improved compared with RQ 2.

(II) In the optimized planting strategy, the planting area of stagnant crops was significantly controlled. This is due to the fact that the model more fully considers market demand fluctuations and crop substitutability in the analysis process. Lagging crops usually face the problem of low market demand and poor sales[11], and excessive planting not only occupies limited arable land resources, but also may lead to waste of resources.

(III) In the model of Problem 3, the planting proportion of complementary crops increases, which largely improves the stability of the overall return. Complementary crops are those that can compensate for each other when market demand fluctuates greatly. For example, when the market demand for hot crops is strong, complementary crops can fill in the market gaps of other crops and maintain income stability.

## 5. Results

### 5.1. Simulation Modeling

The model for crop profit maximization was solved in Matlab.

## 5.2. Analysis of experimental results

**Table 2** Each Experimental Results

Different Research Questions	Total Profit
RQ1-1	32459661
RQ1-2	37022430
RQ2	39255403
RQ3	40596727

As shown in the table, in line with the normal agriculture and market laws, comparing the total profit of RQ1 and RQ3, it is found that through the optimization methods such as MIP and after considering the complex correlation between crops, this paper is able to effectively balance the relationship between the maximization of revenue and the efficiency of resource utilization, and effectively optimize the planting strategy.

## 6. Conclusions

The paper introduces multiple variables, constraints, and objective functions, which enhance the model's precision but also increase computational complexity. This is particularly challenging for large-scale real-world problems, where computational time and resources may become bottlenecks.

While the paper mentions the types and limitations of greenhouse cultivation, it offers limited discussion on optimizing crop combinations within greenhouses. This fails to fully leverage the unique advantages and utilization value of greenhouse systems.

Through optimization methods like mixed-integer programming, the paper effectively balances profit maximization with resource utilization efficiency. It successfully addresses waste caused by overproduction and maintains profit optimization even under price reductions. The innovative introduction of crop substitutability and complementarity fully accounts for complex crop interactions, enhancing the flexibility and rationality of planting schemes. The model design incorporates extensive data, enhancing practical applicability through historical analysis and market demand forecasting. The results offer strong real-world guidance, enabling site-specific crop selection and optimized planting strategies. This facilitates field management, boosts production efficiency, and mitigates planting risks stemming from various uncertainties.

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