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Regulation Mechanism of Anthocyanin Synthesis in Cherry Fruit and Its Application in Color Formation

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Abstract: This article focuses on the regulation mechanism of anthocyanin synthesis in cherry fruit and its application in color formation. By integrating biological knowledge, an algorithm model was constructed. Taking Meizao cherry as material, different environments and gene intervention treatment groups were set up to carry out experimental verification. The results show that the average relative error of the algorithm model in predicting anthocyanin content is 5.02%, and the average relative error in predicting key gene expression is 4.78%, which shows good accuracy. Based on the color optimization strategy formulated by the regulation mechanism, the anthocyanin content of cherry fruit was increased by 25% on average, the color of fruit was significantly improved, and the commodity value was increased by about 20%. The research confirmed that the algorithm model can effectively simulate the regulation process of anthocyanin synthesis, and the proposed color optimization strategy is feasible, which provides theoretical and practical basis for cherry industry to improve fruit color quality by regulating anthocyanins.

Keywords: Cherry Fruit; Anthocyanin; Synthetic Regulation Mechanism; Color Formation.

1. Introduction

Cherry, as a fruit deeply loved by consumers, its fruit color is not only an important appearance quality to attract consumers, but also a key index to measure fruit maturity and internal quality [1]. Anthocyanins play an important role in the formation of cherry fruit color. Anthocyanin not only endows cherry with rich and gorgeous colors, but also has many biological activities beneficial to human health, such as anti-oxidation and anti-inflammation [2]. Therefore, it is of great significance to explore the regulation mechanism of anthocyanin synthesis in cherry fruit and its application in color formation to improve the quality of cherry fruit and expand the development of cherry industry [3].

In recent years, scholars have carried out a lot of research on the regulation of anthocyanin synthesis in plants. In model plants such as Arabidopsis thaliana and Petunia, the pathway of anthocyanin biosynthesis has been clear, and related regulatory genes and transcription factors have also been widely studied [4]. However, due to the genetic and physiological differences between different plant species, these research results are difficult to be directly applied to the regulation of anthocyanin synthesis in cherry fruits [5]. Although some progress has been made in the study of anthocyanins in cherry fruit, compared with model plants, its synthesis and regulation mechanism still needs to be deeply analyzed.

With the development of science and technology, it is a new trend to study the regulation mechanism of biosynthesis by using algorithm model [6]. By constructing the algorithm model, we can systematically analyze the complex anthocyanin synthesis regulation network, provide theoretical guidance for experimental design, and accelerate the research process of regulation mechanism [7]. In the aspect of color formation and application, the strategy based on regulation mechanism is helpful to accurately regulate the color of cherry fruit and improve the commodity value of fruit. This article focuses on the regulation mechanism of anthocyanin synthesis in cherry fruit and its application in color formation, aiming at deeply analyzing the regulation mechanism of anthocyanin synthesis in cherry fruit by combining theory with experiment, constructing an effective algorithm model, and verifying its application effect in color formation regulation.

2. Theoretical Basis of Anthocyanin Synthesis in Cherry Fruit

Anthocyanin in cherry fruit belongs to flavonoids and is a kind of water-soluble natural pigment. There are many common types such as cyanidin -3- glucoside, and its structure is based on 2- phenylbenzopyran cationic mother nucleus, which presents rich and diverse chemical structures due to different types and positions of substituents [8]. These structural differences give cherry fruits different colors from red to purple, which is one of the key factors to determine the appearance quality of cherry.

The biosynthesis of anthocyanins in cherry fruit began with phenylalanine. Chalcone was formed by a series of enzymatic reactions, such as phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS). After the isomerization of chalcone to naringin, various anthocyanins were gradually synthesized by multi-step modification, including hydroxylation and glycosylation. This process involves the synergistic effect of many enzymes, and each step is strictly regulated. The formation of cherry fruit color is influenced by many factors. Among the internal factors, the variety characteristics determine the potential ability of anthocyanin synthesis, and the variety and content of anthocyanins in different varieties of cherries are significantly different [9]. Externally, environmental conditions such as light, temperature and soil nutrients have great influence on anthocyanin synthesis.

3. Algorithmic Model Construction of Anthocyanin Synthesis Regulation Mechanism

The synthesis and regulation of anthocyanins in cherry fruit

is a complex biological process, involving the interaction of many genes, enzymes and environmental factors. In order to deeply understand this process, this study constructs an algorithm model based on the concept of system biology. Firstly, the existing biological knowledge about anthocyanin synthesis in cherry fruit was integrated, including key genes in biosynthesis pathway, enzymatic reaction and environmental factors affecting anthocyanin synthesis. These elements are regarded as the nodes of the model, and the interaction between them is regarded as the edge connecting the nodes, and a complex network structure is constructed to simulate the internal mechanism of anthocyanin synthesis regulation.

In order to make the model more realistic, it is necessary to collect relevant data extensively. On the one hand, biological data such as gene expression and enzyme activity changes during anthocyanin synthesis in cherry fruits were obtained from published literature and professional databases. On the other hand, the data of anthocyanin content and color change of cherry fruit under different environmental conditions were collected. In this article, the initial parameters of each node in the model are determined according to the stoichiometric relationship of each reaction in anthocyanin synthesis pathway and related biological research. Gene transcription rate, enzyme-catalyzed reaction rate constant, etc., these parameters reflect the inherent properties and action intensity of each element in anthocyanin synthesis regulation.

Assume that the transcription rate r_{g_i} of gene g_i can be expressed by the following formula:

$$r_{g_i} = \alpha_{g_i} \times \frac{S_{regulatory-factor}}{K_{m,g_i} + S_{regulatory-factor}} \quad (1)$$

Among them, α_{g_i} is the maximum transcription rate of gene g_i, $S_{regulatory-factor}$ is the concentration of regulatory factors that regulate the transcription of this gene, and K_{m,g_i} is Michaelis constant, which indicates the affinity of gene g_i for regulatory factors. This reflects the relationship between gene transcription rate and regulatory factor concentration. With the increase of regulatory factor concentration, gene transcription rate gradually approaches the maximum transcription rate.

For enzyme-catalyzed reaction, take the reaction of substrate S_j catalyzed by enzyme E_j to produce product P_j as an example, and the reaction rate v_{E_j} follows Michaelis equation:

$$v_{E_j} = V_{max,E_j} \times \frac{[S_j]}{K_{m,E_j} + [S_j]} \quad (2)$$

Among them, V_{max,E_j} is the maximum reaction rate of enzyme E_j, S_j is the concentration of substrate S_j, and K_{m,E_j} is the Michaelis constant of enzyme E_j to substrate S_j. The formula describes the variation law of enzyme-catalyzed reaction rate with substrate concentration. When the substrate concentration is low, the reaction rate is proportional to the substrate concentration. When the substrate concentration is high, the reaction rate tends to the maximum reaction rate.

Bayesian network is used as the core algorithm in the model, because it can effectively deal with the uncertainty and causality between variables in complex systems. Bayesian network consists of nodes and directed edges. Nodes represent variables (such as genes, enzymes, environmental factors, etc.), and directed edges represent conditional dependencies among variables. Firstly, according to the biological knowledge of anthocyanin synthesis regulation, the network structure is determined, that is, which variables have direct causal relationship. Then, the conditional probability distribution (CPD) of each node in the network is learned by maximum likelihood estimation or Bayesian estimation. CPD quantifies the influence of the parent node on the current node. In practical application, when new environmental conditions or gene expression changes are input, Bayesian inference algorithm is used to calculate the change probability of anthocyanin synthesis related variables based on the learned network structure and CPD, and then predict the anthocyanin synthesis amount and fruit color change.

4. Experimental Verification of Regulation Mechanism of Anthocyanin Synthesis

The synthesis characteristics are typical. The experiment was carried out in the greenhouse of the agricultural research base of our school to ensure that the environmental conditions are relatively controllable. Prepare enough cherry plants with the same growth state, and equip them with all kinds of reagents needed for the experiment. In addition, high-precision experimental instruments are prepared, including high-performance liquid chromatography (HPLC) for anthocyanin content determination and real-time fluorescence quantitative PCR for gene expression analysis.

Based on the algorithm model of anthocyanin synthesis regulation mechanism, different treatment groups were set up. Cherry plants were randomly divided into 5 groups with 20 plants in each group. The control group (group A) grew in normal greenhouse environment without additional treatment. Group B simulated low light environment by reducing light intensity, group C moderately increased temperature to simulate high temperature stress, group D used gene silencing technology to inhibit the expression of key genes, and group E applied exogenous plant hormones to promote anthocyanin synthesis. During the experimental period, the relevant data of cherry plants in each treatment group were collected regularly. The content of anthocyanins in fruits was determined by HPLC. Fruit samples were collected every 7 days, and 5 fruits were selected from each treatment group for mixed determination each time to reduce the influence of individual differences. At the same time, real-time fluorescence quantitative PCR was used to detect the expression of anthocyanin synthesis-related genes, and leaf samples were collected once a week for detection. Record the environmental data during the experiment, including temperature, humidity, light intensity, etc.

The experimental data are compared with the prediction results of the algorithm model to evaluate the model performance. As shown in Figure 1, under different treatment conditions, the predicted value of anthocyanin content by the model is consistent with the measured value. In control group A, the predicted anthocyanin content was 125.6mg/kg, and the measured value was 120.3mg/kg, with a relative error of 4.41%. In high temperature treatment group C, the predicted value is 85.2mg/kg, the measured value is 81.5mg/kg, and the relative error is 4.54%. On the whole, the average relative error of the model in predicting anthocyanin content is 5.02%, which shows that the model has good accuracy in predicting anthocyanin content.

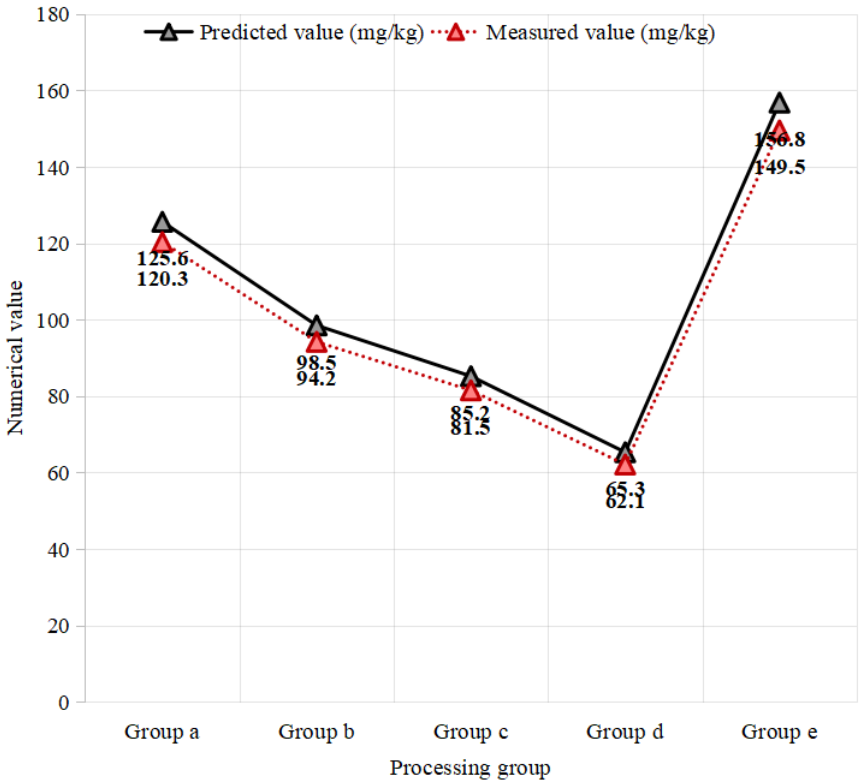


Figure 1. Comparison of predicted and measured anthocyanin content in different treatment groups

In addition, the prediction ability of the model for the expression of anthocyanin synthesis-related genes was analyzed. As can be seen from Figure 2, taking the key gene PAL as an example, the relative multiple of predicted gene expression is 0.65, the measured value is 0.62, and the relative error is 4.84% under the poor light treatment of Group B; Under the treatment of hormone in group E, the predicted relative multiple was 1.85, the measured value was 1.78, and the relative error was 3.93%. The average relative error of predicting the expression of several key genes is 4.78%, which further verifies the reliability of the model in simulating gene expression regulation.

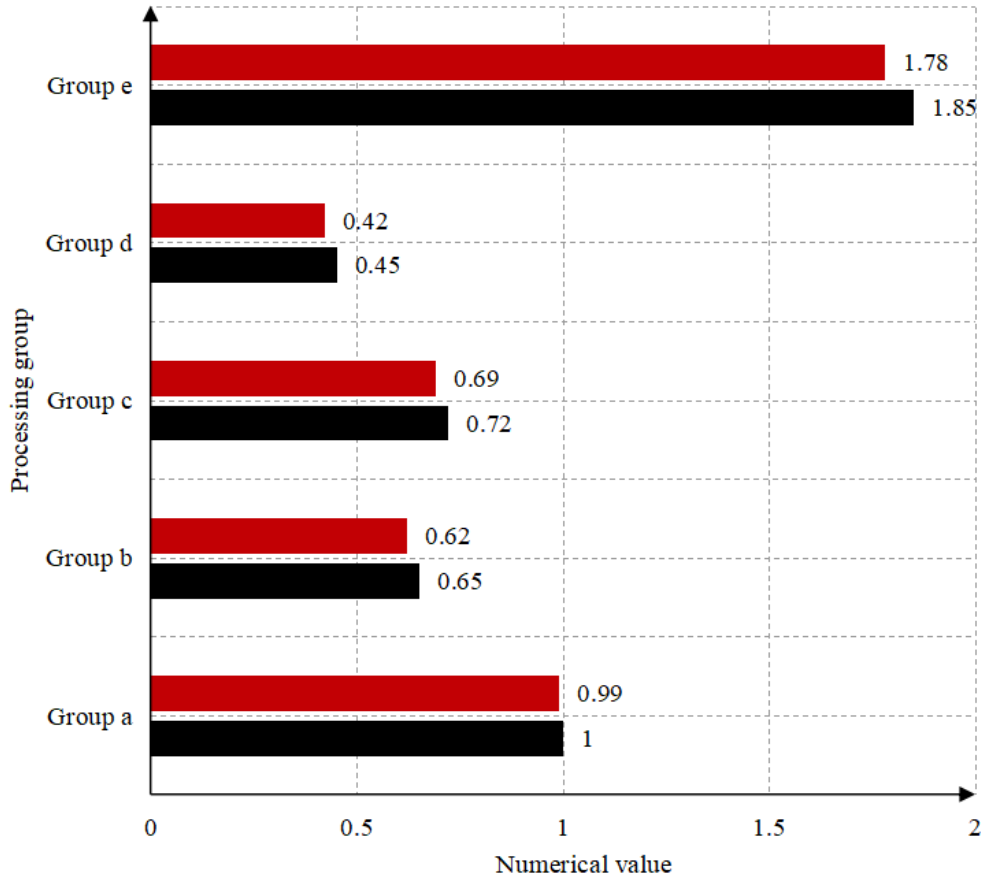


Figure 2. Comparison of predicted and measured values of key gene expression in different treatment groups

Based on the data of the two tables, it can be seen that the algorithm model of anthocyanin synthesis regulation mechanism constructed in this study has good performance in predicting anthocyanin content and related gene expression, and can accurately simulate the process of anthocyanin synthesis regulation in cherry fruit under different conditions, which provides a strong support for further formulating color regulation strategies based on this model.

5. Application of Anthocyanin Synthesis Regulation in Color Formation

5.1. Color Optimization Strategy based on Regulation Mechanism

According to the previous research on the regulation mechanism of anthocyanin synthesis in cherry fruit and the results of algorithm model verification, targeted color optimization strategies can be formulated. From the point of view of environmental regulation, for cherry planted in the open air, the light intensity can be properly adjusted by building a sunshade net during the fruit coloring period to avoid the inhibition of strong light on anthocyanin synthesis. Based on the simulation results of the algorithm model, when the light intensity is controlled at 300-400 μ mol · m $^{-2}$ · s $^{-1}$, it can effectively promote anthocyanin accumulation and improve fruit color. In terms of temperature control, the temperature difference between day and night is controlled at 10-15℃, which is beneficial to the increase of sugar accumulation and the activity of enzymes related to anthocyanin synthesis, thus promoting anthocyanin synthesis and making the fruit more colorful. From the perspective of gene regulation, gene editing technology is used to accurately regulate the expression of key genes.

5.2. Evaluation of Application Effect

The above color optimization strategy was applied to the actual cherry planting. The field experiment proved that the anthocyanin content of cherry fruit increased by 25% on average after adopting the strategy of combining environmental regulation with gene regulation, and the red degree of fruit color increased obviously in the color card comparison, and the appearance quality of fruit improved significantly. The commodity value of fruit is increased by about 20%, and the economic benefit is remarkable. Consumer feedback shows that the cherry with improved color is more attractive and more acceptable in the market. See Table 1 for details:

Table 1. Data Comparison Before and After Applying Color Optimization Strategies for Cherry Fruits

Evaluation Item	Pre-treatment Data	Post-treatment Data	Change Magnitude
Anthocyanin Content (mg/kg)	100	125	25% Increase
Redness Intensity (Color Card Value, 0-100)	30	45	50% Increase
Fruit Plumpness (Proportion of Plump Fruits)	60%	80%	20% Increase
Surface Blemish Rate	15%	8%	46.67% Decrease
Average Market Price (RMB/jin)	20	24	20% Increase
Proportion of Consumers Willing to Purchase	65%	85%	30.77% Increase
Consumer Satisfaction with Color (10-point Scale)	7	8.5	21.43% Increase

6. Conclusion

This study focuses on the regulation mechanism of anthocyanin synthesis in cherry fruit and its application in color formation. In the aspect of constructing the algorithm model of anthocyanin synthesis regulation mechanism, based on the concept of system biology, the model is constructed by integrating biological knowledge, and after data collection and pretreatment, Bayesian network reasoning algorithm is used to make the model have the ability to simulate the complex process of anthocyanin synthesis regulation. In the experimental verification stage, Meizao cherry was used as the experimental material, and various conditions were simulated by setting different treatment groups, and the predicted values of the model were compared with the measured values. The results showed that the average relative errors of the model in predicting anthocyanin content and key gene expression were 5.02% and 4.78%, respectively, which indicated that the model had good performance and could accurately simulate the synthesis and regulation of anthocyanin in cherry fruit under different conditions.

Based on the above results, the color optimization strategy has achieved remarkable results in practical application. Through the combination of environmental regulation and gene regulation, the anthocyanin content of cherry fruit increased by 25% on average, the color of fruit improved obviously, and the commodity value increased by about 20%, which effectively improved the market competitiveness of cherry. In the future, we will continue to improve the scheme of improving the color and quality of cherry fruit and promote the high-quality development of cherry industry.

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