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Genetic regulation mechanism and breeding strategy of pepper quality and stress resistance

Shiyu Ouyang[#,*], Xinyue Zhang[#], Zuoduo Wu, Wei Zhou, Yixin Zhuang

Hunan Agricultural University, Changsha, Hunan, 410128, China
[#]These authors contributed equally to this work.

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Abstract: As an important cash crop, pepper quality and stress resistance directly affect the production and market competitiveness. This paper reviews the genetic regulation mechanism of pepper quality and stress resistance and different strategies applied in pepper breeding. Based on the analysis of relevant literature, the main genes and their regulatory networks affecting the quality and stress resistance of capsicum were discussed, and the key roles of transcription factors, plant hormones and signaling pathways in these processes were emphasized. In order to cope with climate change and market demand, future breeding strategies should focus on the mining and utilization of genetic diversity to improve the quality and stress resistance of pepper.

1. Introduction

Chilli is one of the important crops globally and is widely grown in tropical and subtropical regions. As a major global condiment and vegetable, chilli peppers feature prominently in the diets of many countries. Its unique flavour and colour make it used not only to add flavour to dishes but also to enhance visual appeal. In recent years, as people have become more health-conscious, chilli has been favoured by an increasing number of consumers for its rich nutritional content. In addition, chilli is also believed to have some medicinal value, helping to improve blood circulation and enhance immunity.

However, chilli production faces many challenges. With global climate change, the frequency and intensity of droughts, floods, pests and diseases are increasing, putting enormous pressure on chilli growth and yield. Traditional growing methods are often overwhelmed in dealing with these adversities, making it imperative to improve the resilience of chillies. At the same time, consumer demand for chilli quality is also increasing, and there is a growing demand for high-quality, high-nutritional value chilli varieties, which further promotes the process of chilli breeding research.

In recent years, with the development of genomics and molecular biology technology, researchers have gradually revealed the genetic basis and physiological mechanisms of chilli, which provides new ideas for improving the quality and stress resistance of chilli[1]. The quality and stress tolerance of chilli is a complex trait regulated by multiple genetic factors and their interactions. In recent years, with the development of molecular biology and genomics, researchers have gradually revealed the genetic basis of chilli quality and stress tolerance, including the identification of key genes, signalling pathways and metabolic pathways. In addition, the application of modern breeding technologies (e.g., genome editing, marker-assisted selection, etc.) has greatly accelerated the process of genetic improvement of chilli, providing strong support to meet future market demands and environmental challenges [2][3][4].

2. Genetic regulatory mechanisms of quality and resistance in chilli peppers

2.1. Genetic regulation of chilli quality Genetic basis of quality traits such as chilli fruit colour, spiciness and nutrient content

Resistance and quality traits in chillies are usually under polygenic control, with many traits being the result of the combined action of several genes. These genes are improved through genetic variation, selection and artificial breeding. Through methods such as genome-wide association analysis (GWAS) and genomic selection (GS), researchers have identified a number of key genes associated with stress tolerance.

2.2. Genetic regulation of chilli resistance Genetic mechanisms of chilli resistance to heat, drought, salt stress and disease

2.2.1. Mechanisms of resilience under high temperature stress

(1) Expression of heat shock proteins (HSPs): HSPs are a class of protective proteins that enhance plant tolerance to heat stress.

(2) Activation of the antioxidant system: high temperatures generate large amounts of reactive oxygen species (ROS), and chilli reduces damage by enhancing the activity of antioxidant enzymes (e.g. superoxide dismutase, catalase, etc.) to scavenge ROS.[5]

2.2.2. Mechanisms of resilience to drought stress

(1) Improvement in water use efficiency: chillies can improve water uptake and use efficiency by regulating the growth, development and function of the root system.

(2) Expression of drought-related genes: up-regulated in response to drought stress in plants, involved in the regulation of stomatal opening and root development, etc.

(3) Ion exclusion and transport: salt stress-induced Na^+ excess is taken up by chilli peppers through ion-selective and exclusionary mechanisms, which can reduce the entry of Na^+ through selective uptake by the root system, while increasing the accumulation of K^+.

(4) Activation of salt-resistant genes: e.g., the SOS (Salt Overly Sensitive) gene pathway involves a response mechanism to high-salt environments by regulating intracellular Na^+ and K^+ concentrations.[6]

2.2.3. Genetic mechanisms of disease resistance

(1) Role of resistance genes: R genes (disease resistance genes) are essential for disease resistance in chilli, recognising the characteristics of the pathogen and initiating the plant's defence mechanisms.

(2) Activation of the plant's immune system: Enhancement of its own resistance to diseases through the synthesis of pharmacodynamic substances such as flavonoids and phenylpropanoids.

2.3. Discovery and functional analysis of key resistance genes in chilli peppers

2.3.1. CaNAC2c

CaNAC2c belongs to the NAC (NAM, ATAF, and CUC) family of transcription factors. In plants, NAC transcription factors play important roles in regulating plant responses to a variety of environmental stresses.The expression of CaNAC2c was correlated with drought and salt stresses in plants, and experimental results showed that its expression was significantly up-regulated under adversity stress. Functional studies revealed that CaNAC2c enhanced the tolerance of pepper to drought and salt stress by regulating the expression of antioxidant enzymes and the synthesis of osmoregulatory substances [7][8].

2.3.2. CaCDPK29-CaWRKY27b module

CaCDPK29 (calcium-dependent protein kinase) is an important signal transduction molecule that senses changes in intracellular calcium ions, which in turn regulates the expression of specific genes.CaWRKY27b belongs to the WRKY family of transcription factors, which are involved in the regulation of disease resistance and stress tolerance in plants.The interaction between CaCDPK29 and CaWRKY27b forms a regulatory module that capable of responding to environmental stresses and promoting the expression of resistance genes, such as those related to disease resistance and stress tolerance[9][10].

2.4. Role of transcription factors and signal transduction pathways in the regulation of pepper resistance

2.4.1. Transcription factor

NAC transcription factors: these factors play a central driving role in response to drought and salt stress. They regulate the expression of antioxidant- and osmoprotection-related genes and improve plant tolerance [11].

WRKY transcription factors: members of the CaWRKY27, CaWRKY20 and other families play key roles in plant responses to diseases and physiological stresses. They enhance overall plant resistance by regulating the expression of defence genes (e.g. pathogen-related genes) and adversity-related genes [12].

2.4.2. Signaling pathway

Abscisic acid (ABA) signalling pathway: ABA is a key hormone in plant response to drought and other adversities [13]. Its signalling pathway can activate multiple downstream genes (e.g. DREB & MYB genes) in the cell through ABA receptor binding, promoting stomatal closure, water retention and stress-resistant protein synthesis, thus improving drought resistance in chilli.

Calcium signalling pathway: calcium acts as a secondary messenger and as an important molecule for signalling under adverse conditions.CaCDPK (calcium-dependent protein kinase) is essential in calcium signalling. In chilli, calcium signalling activates transcription factors associated with the adversity response, which in turn enhances stress tolerance.

2.4.3. Interaction of transcription factors with signalling pathways

Mutual regulation: transcription factors can act as downstream effectors of signalling pathways, responding to environmental stimuli and altering gene expression patterns. This enables plants to adapt to adversity. At the same time, activation of the signalling pathway can also promote the expression of specific transcription factors.

Feedback regulation: under adverse conditions, some components of the signalling pathway may in turn regulate the expression of transcription factors to maintain homeostasis and adaptation within the plant.

3. Breeding strategies for chilli peppers

3.1. Genetic diversity analysis of germplasm resources and their application in breeding

3.1.1. Genetic diversity analysis

By analysing the genetic diversity of germplasm resources, it is possible to identify genetic differences, phenotypic differences and adaptive characteristics among different individuals, which helps to understand the evolutionary history of species and their ecological adaptive capacity.

Molecular marker techniques: genome level analysis using microsatellite DNA markers (SSR), single nucleotide polymorphisms (SNP), and random amplified polymorphic DNA (RAPD).

Morphological and physiological characteristics: Trait analysis by comparing external morphology, reproductive characteristics, growth habit, etc. of germplasm samples.

3.1.2. Applications in Breeding

Resistance analysis: Diversity studies can identify germplasm with excellent traits such as resistance to pests and diseases, tolerance to adversity, etc., and provide a basis for crop improvement.

Resource conservation and management: Understanding the genetic diversity of germplasm resources will help to develop effective biodiversity conservation strategies and ensure an adequate genetic base for future responses to climate change and environmental pressures.

Regeneration and breeding programmes: By analysing information on the genetic diversity of different germplasm, germplasm banks and breeding programmes can be designed more scientifically to ensure the sustainable use of germplasm resources.

3.2. Chilli breeding technology traditional breeding methods in chilli quality and resistance improvement

3.2.1. Cross-breeding

(1) Application in chilli quality improvement: enhancement of taste and flavour, spiciness and aroma.

(2) Application in resistance improvement: resistance to pests and diseases, tolerance to adversity.

3.2.2. Backcross breeding

(1) Application in chilli quality improvement: retaining good traits and improving nutrient content.

(2) Application in resistance improvement: enhancement of resilience

3.2.3. Mutagenesis breeding

(1) Application in chilli quality improvement: introduction of new traits to improve fruit traits.

(2) Application in resistance improvement: Improvement of disease resistance and strong

tolerance to adversity.

3.3. Selection and breeding cases of disease-resistant chilli varieties

In 2000, Wang Lihao in Shandong, a greenhouse research, accidentally found a few sweet pepper samples appeared pepper light mottle disease. Chilli light mottle disease is a viral disease, basically no specific drugs can cure, mainly by the plant's own resistance. Pepper infestation can lead to a 30% to 100% yield reduction. Through further research, Wang Lihao and his team predicted that this sweet chilli disease will occur in large areas in China. In order to avoid this sweet chilli disease in China on a large scale Wang Lihao thought of a way to breed new sweet chilli varieties that can resist chilli light mottle disease. Next, Wang Lihao and his team and the virus race, and constantly collect the introduction of foreign germplasm resources, for the selection and breeding of disease-resistant varieties to prepare. He established a combined method of conventional breeding technology with biotechnology and disease resistance identification technology, and made a breakthrough to innovate seven excellent parental self-inbred lines. During the outbreak of chilli light mottle disease in China in 2015, a dozen disease-resistant varieties bred by Wang Lihao's team came to the rescue in time, which not only resisted the proliferation of chilli light mottle disease, but also put China's breeding technology in this field ahead of the international community. Wang Lihao and the team bred the first domestic resistance to the new epidemic disease chilli light mottle virus disease (PMMoV) and tomato spotted wilt virus disease (TSWV) and other five diseases and high quality in pepper 105 and other six series of new varieties. The results fill the gap of China's lack of varieties resistant to these two new popular diseases, the results of the breakthrough in the "neck problem", and has produced huge social and economic benefits [14][15][16].

3.4. Selection and breeding cases of early-maturing chilli varieties

Hengyang Vegetable Research Institute chilli group in the spring of 2013 in the ambrosia tip chilli field found five mutant single plants, and six generations of self-crossing directional selection, and ultimately selected two different types of excellent strains, and long-fruiting type of varieties named Hengyang pepper No.1[17].

Table 1 Experimental yield results of Hengyang pepper No.1 multi-point regional test

site	age	Early yield/(kg/667 ㎡)		Compared with CK±%	Totaloutput/(kg/667 ㎡)		Compared with CK±%
		Hengyang pepper No.1	Fudijian pepper(CK)		Hengyang pepper No.1	Fudijian Pepper(CK)	
Hengyang	2018	1125.4**	954.6	17.89	2012.8**	1715.1	17.36
	2019	986.2**	832.1	18.52	1868.8**	1613.4	15.83
Yueyang	2018	1045.2**	894.7	16.82	1925.7**	1612.9	19.39
	2019	1105.2**	964.1	14.64	1987.5**	1802.5	10.26
Changde	2018	904.8**	802.3	12.78	1787.6**	1508.7	18.49
	2019	975.2**	841.9	15.83	1847.0**	1627.3	13.50
Chenzhou	2018	1068.2**	973.2	9.76	1965.2**	1712.4	14.76
	2019	946.2**	802.8	17.86	1828.1**	1634.1	11.87
Changsha	2018	973.2**	825.3	17.92	1924.1**	1625.8	18.35
	2019	987.9**	848.3	16.46	2012.4**	1702.2	18.22
average		1011.75	873.93	15.85	1915.92**	1655.44	15.30

Hengyang pepper No.1 is very early in ripening, with 6 to 8 nodes, short and compact plant, ox horn shaped fruit, many fruits, and strong resistance to adversity. Fruit expansion fast, strong fruiting force, fruit longitudinal diameter 17.0 cm, fruit transverse diameter 2.3 cm, flesh thickness 0.27 cm, the average quality of a single fruit 19.6 g, commercial mature fruit green, physiological maturity of the fruit bright red, fruit surface smooth, spicy taste medium, meat crisp, soft, good flavor; Hunan spring and summer planting from planting to the beginning of the harvest of 42 d or so; plant hardiness is strong, good resistance to disease, anthracnose has not been found in the field, Epidemic disease, virus disease; suitable for the Yangtze River basin open field and early spring and autumn extension after the facility cultivation.

4. Conclusions

The application of genetic analysis and molecular markers will enable more efficient selection of target traits in future chilli breeding [18][19]. At the same time, a deeper understanding of the genetic mechanisms of chilli in terms of quality and stress tolerance will provide the basis for scientists to be able to breed more high-quality, high-yielding, and stress-tolerant chilli varieties to meet the growing market demand and to face the challenges of agriculture in the face of climate change. Achievements in chilli quality and resilience research and the integration of breeding strategies will drive the sustainable development of the chilli industry and provide strong support for global agricultural production [20][21].

Breeding tools allow for the selection and breeding of high-yielding varieties of chilli. These varieties show higher fruit yields, good growth habits and adaptability to grow in different climatic and soil conditions [22][23]. The growth characteristics of chillies can be improved through genetic engineering and traditional breeding techniques. The quality of chilli is not only in terms of yield, but also in terms of its flavour, colour, spiciness and nutrient content. The scientific breeding process can screen out varieties with excellent fruit quality and higher nutritional value to improve the market competitiveness of chilli. Breeding results in chilli varieties that are better able to withstand diseases, thus allowing the fruit to maintain higher quality and longer shelf life in the market. Chilli is often exposed to adversities such as drought, cold and salinity during its growth period, and through breeding it is possible to produce chilli varieties that are able to maintain high yields and quality in spite of these adversities. This is important to protect and stabilise agricultural production. By improving the resilience of chilli, it is possible to increase the efficiency of its use of resources such as water, fertiliser and sunlight, enabling good growth in relatively resource-poor environments. In the context of global climate change, chilli breeding can also help growers to adopt crop varieties that are better adapted to extreme weather, reducing losses due to climate change and ensuring sustainable agricultural development. Pepper breeding plays a crucial role in boosting agricultural production, improving food quality and enhancing ecological resilience, and is an indispensable part of modernising and sustaining agriculture[24][25][26].

The future direction of chilli breeding involves not only new technological tools and research methods, but also a greater focus on market demand and sustainable development. Improving the efficiency and quality of chilli breeding by effectively combining modern technology with traditional agriculture will bring greater potential and opportunities for global chilli production and consumption [27].

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