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The Effect and Mechanism Analysis of High Temperature on Rice Pollen Development and Pollination

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Abstract This study aims to delve into the impact of high temperature on rice pollen development and pollination processes, along with its underlying mechanisms. With the ongoing global temperature rise, high-temperature stress poses a severe challenge to rice production. We scrutinize the fundamental processes of rice pollen development, with a particular focus on the temperature sensitivity during critical developmental stages. The study extensively analyzes the involvement of hormone signaling pathways in rice under high-temperature conditions, highlighting the variations and physiological significance of hormones such as ABA, GA, and ethylene. At the molecular level, we delve into the regulation of rice protein synthesis and metabolism under high temperature, revealing alterations in protein synthesis rates and composition. Moreover, we propose recommendations for future research and agricultural practices, emphasizing the cultivation of high-temperature-adaptive rice varieties through genetic improvement and agricultural management strategies. This research provides a theoretical foundation for a profound understanding of the impact of high temperature on rice reproductive processes, contributing to the achievement of sustainable agriculture and global food security.

Keywords Rice (*Oryza sativa*); High-temperature stress; Pollen development; Hormone signaling pathways; Protein synthesis

Against the backdrop of global climate change, rice (*Oryza sativa*), one of the main sources of food, is facing unprecedented challenges. The increase in temperature and frequent occurrence of extreme weather events have had an undeniable impact on the growth, development, and yield of rice. Especially the reproductive process of rice, although crucial, appears fragile under high temperature conditions. The aim of this study is to investigate in depth the effects of high temperatures on rice pollen development and pollination, reveal their potential mechanisms, and provide scientific basis for future agricultural responses to climate change.

Rice, as one of the three major staple foods in the world, not only provides abundant nutrition for humanity, but also serves as the livelihood foundation for hundreds of millions of people. However, in recent years, with the continuous rise of global temperatures, high temperature events have become more frequent and extreme. This poses a serious challenge to the growth and yield of rice. High temperatures not only directly affect the photosynthesis and physiological activities of rice, but also have a negative impact on pollen development and pollination during the reproductive process, ultimately threatening global food security.

In this context, the aim of this study is to gain a deeper understanding of the effects of high temperature on rice pollen development and pollination, as well as the molecular mechanisms underlying these effects. We will explore the basic process of rice pollen development, focusing on key growth stages and developmental steps. We will also analyze in detail the effects of high temperature on rice pollen development, including changes in pollen vitality, survival rate, pollen tube growth, and direction regulation (Hsu et al., 2021). Meanwhile, we will conduct in-depth research on the impact of high temperature on rice pollination, exploring the success rate of pollination, interaction between stamens and pistils, and changes in pistil development. In addition, we will focus on the molecular mechanisms of high temperature on the development of rice reproductive organs, including gene expression, protein synthesis and metabolism, and the involvement of hormone signaling pathways.

Through in-depth research on these aspects, we hope to reveal the specific effects of high temperature on the reproductive process of rice, and provide more accurate decision-making support for future agricultural production. In addition, we will also examine rice varieties that are adapted to high temperatures, delve deeper into the genetic basis of high temperature tolerance, and explore the application prospects of genetic engineering and breeding methods in improving rice high temperature tolerance. Through these studies, we are expected to provide new ideas and solutions for sustainable development and food security issues in the agricultural sector.

1. Development Process of Rice Pollen

1.1 Basic process of pollen development

Pollen development is a crucial link in the reproductive process of rice plants, directly related to the reproductive success and yield of rice. This complex process typically involves several key growth stages, each of which is highly sensitive to the external environment and internal regulatory factors while ensuring the smooth development of pollen. The first stage of pollen development is the production of pollen mother cells. In the flower buds of rice, anthers are the main site of pollen development, containing a large number of pollen mother cells. These mother cells undergo meiosis to produce four haploid pollen spores. The accuracy of this process is crucial for subsequent pollen development, and high temperatures often have a direct impact on this stage of meiosis.

Next is the differentiation and development of pollen spores. Pollen spores are divided into two types, which produce two different types of cells: one is pollen mother cells with reproductive functions, and the other is nutrient rich cells responsible for providing support and nutrients. This stage is influenced by hormone regulation, especially the balance between auxin and gibberellin, to ensure the normal development of pollen.

In the third stage of pollen development, pollen mother cells further differentiate into two different cells, forming mature pollen grains. This process involves the synthesis of cell walls, the movement of the nucleus, and the formation of the plasma membrane. High temperature environments may interfere with these cellular processes, leading to abnormal pollen morphology or functional defects (Lewandowska et al., 2022).

Finally, mature pollen grains are dispersed to the external environment through anther cracks, waiting for the pollination process to take place. The success of this process depends on the accurate development of the aforementioned stages, and any abnormality in any stage may have an impact on the final reproductive success. The basic process of pollen development involves multiple complex cytological and biochemical events. As one of the external environmental factors, high temperature needs to be studied in depth to fully understand the impact mechanism of high temperature on the rice reproductive system. Through in-depth research on pollen development, we can provide more accurate decision support for agricultural production and help agricultural producers better adapt to constantly changing climate conditions.

1.2 Temperature sensitivity during critical developmental stages

The key stages of rice pollen development are crucial throughout the entire growth process, and the development of these key stages is often highly sensitive to temperature. In high-temperature environments, the normal development of pollen is directly threatened, which may lead to disruption of the reproductive system and ultimately affect rice yield. The meiosis of pollen mother cells is the initial stage of pollen development and one of the most sensitive stages. High temperature conditions may interfere with the progress of meiosis, leading to abnormal chromosome separation or uneven distribution, thereby affecting the genetic stability of subsequent pollen. The negative impact of this phenomenon on pollen development is that abnormal chromosome separation may lead to abnormal genetic material carrying in pollen, thereby affecting its normal function.

The differentiation and development process of pollen spores also exhibit sensitivity to high temperature, which is influenced by hormone regulation. High temperature may disrupt the balance of hormones, thereby affecting the normal development of pollen spores. Hormones such as auxin and gibberellin play crucial roles in regulating pollen differentiation and development, and high temperatures may trigger abnormal expression of these hormones, ultimately leading to hindered or incomplete development of pollen spores (Devireddy et al., 2021).

The formation of mature pollen grains also exhibits certain sensitivity under high temperature conditions, which involves key processes such as cell wall synthesis, nuclear movement, and plasma membrane formation. High temperature may interfere with these cellular processes, leading to abnormal morphology or functional defects in mature pollen grains.

Therefore, the temperature sensitivity of high temperature to rice pollen development is not only reflected in a specific stage, but also runs through the entire development process. The existence of temperature sensitivity makes rice more susceptible to adverse effects from the external environment under high temperature conditions, thereby increasing the uncertainty of successful reproduction. In depth research on temperature sensitivity in key developmental stages is of great theoretical and practical significance for better understanding the mechanism of high temperature on rice reproductive system and providing scientific basis for agricultural production.

1.3 Current research status of rice pollen development

Researchers have conducted in-depth research on the development of rice pollen through multi-level and multi angle methods. Morphologically, researchers observed the meiosis of pollen mother cells, differentiation of pollen spores, and the morphological structure of mature pollen grains through techniques such as microscopy and electron microscopy. These studies reveal the morphological changes of pollen development at different stages, providing a basis for understanding the overall process of pollen development.

Meanwhile, molecular biology research methods are also widely applied in the study of rice pollen development. Through techniques such as transcriptomics and proteomics, scientists have revealed the expression dynamics of a large number of genes during pollen development, especially those involved in key regulation of pollen development. These studies provide rich information for exploring the molecular mechanisms of pollen development (Jiang et al., 2020).

Research under stress conditions has also received much attention, especially the impact of high temperature stress on rice pollen development. A series of experiments have revealed the negative effects of high temperature on key stages of pollen development, including meiosis of pollen mother cells, differentiation of pollen spores, and formation of mature pollen grains. These studies aim to deeply understand the threat of high temperature to the rice reproductive system and provide theoretical basis for cultivating high-temperature resistant rice varieties.

With the continuous advancement of technology, emerging technologies such as single-cell transcriptomics have also begun to emerge in the research of rice pollen development in recent years, enabling us to have a more refined understanding of intercellular differences and regulatory networks in pollen development. Significant progress has been made in the study of rice pollen development, from morphology to molecular level, from normal development to response under stress conditions. Scientists are working to uncover the mysteries of rice reproduction, in order to provide effective strategies for increasing grain yield and agricultural production under climate change.

At present, researchers have conducted extensive research on the development of rice pollen and its regulatory mechanisms, and have achieved a series of important results. Among them, breakthrough progress has been made in the sequencing of rice anther genomes. Through the analysis of rice anther genomes, researchers have discovered multiple genes related to pollen development, which are related to microspore mother cell division, pollen tube growth, and pollen germination (Zhong et al., 2020). At the same time, researchers also studied the functions and biological characteristics of multiple genes related to pollen development through gene knockout and transgenic techniques. These research results provide fundamental support for in-depth analysis of the process and regulatory mechanisms of rice pollen development.

2 The Effect of High Temperature on the Development of Rice Pollen

2.1 Changes in pollen vitality and survival rate

High temperatures have a profound impact on the pollen vitality and survival rate of rice, directly threatening the

reproductive success of plants. Pollen is one of the key factors in the reproduction of rice plants, and its health and vitality are directly related to the success of pollen pollination and the stability of yield. Under high temperature conditions, the vitality of pollen often significantly decreases. Research has shown that an increase in temperature may cause denaturation and oxidation of pollen proteins, thereby affecting the structure and function of pollen particles. Under high temperature conditions, the wax layer on the surface of pollen may change, which in turn affects the water balance and osmotic regulation of pollen particles. These changes directly lead to a decrease in pollen vitality, reducing the success rate of pollen during pollination.

Pollen with vitality contains active peroxidase, which can use hydrogen peroxide to oxidize various polyphenols and aromatic amines and produce color. If the pollen grain is red, it indicates the presence of peroxidase, and the pollen is active and can germinate; If it is colorless, it indicates that it has lost vitality and cannot sprout. The strength of pollen activity can be determined by the color of the pollen. Using rice flowering under normal natural climate conditions as a control, this study investigates the effect of high temperature on rice pollen vitality and seed setting rate.

For example, in a study by Zhao Qihui et al. (2013), they focused on two varieties: heat resistant strain 996 and heat sensitive strain 4628. The results showed that pollen vitality decreased under high temperatures. On the first day of treatment, the pollen vitality of heat resistant strain 996 and heat sensitive strain 4628 decreased by 7.8% and 13.8% respectively compared to the control, with a significant difference. Moreover, as the time of high temperature stress prolonged, the pollen vitality of the two strains continued to decline until the end of treatment, The pollen vitality of heat-resistant strain 996 and thermosensitive strain 4628 decreased by 19.6% and 32.88% compared to the control, with significant differences. During the entire processing period, the pollen vitality of the heat-resistant strain 996 was higher than that of the thermosensitive strain 4628 (Zhang et al., 2008) (Figure 1).

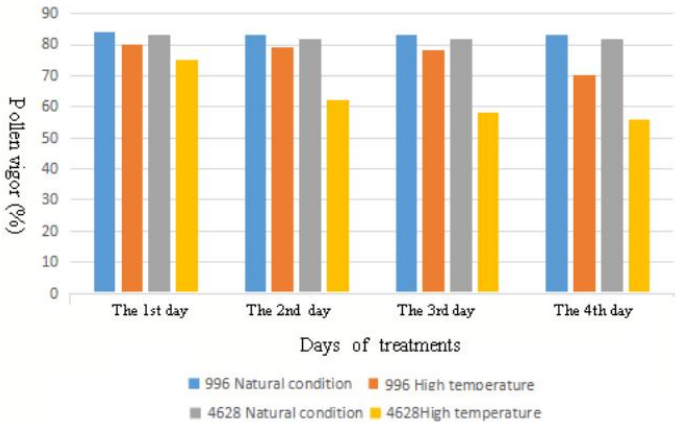

Figure 1 Effects of high temperature stress on rice pollen vigor

In addition to the decrease in pollen vitality, high temperatures also directly affect the survival rate of rice pollen. Under high temperature conditions, the storage capacity of pollen particles decreases, which may lead to the inability of pollen to survive effectively during pollination. Some experiments have shown that under high temperature conditions, pollen may be more prone to losing vitality, and even exhibit higher mortality rates during storage.

2.2 Effect of high temperature stress on the number of pollen grains on rice stigma

High temperature stress has a widespread and significant impact on the reproductive process of rice, one of which is its effect on the number of pollen grains on the stigma. The stigma is a crucial part of rice inflorescence, directly involved in the propagation and pollination process of pollen. In high-temperature environments, the reduction of pollen grains on the stigma may become an important factor in the reduction of rice yield. The seed setting rate of rice depends on the fertilization rate, and normal fertilization first depends on the number of pollen grains on the stigma. If sufficient pollen grains cannot be guaranteed, normal fertilization and seed setting cannot be achieved.

Research has shown that high temperature stress can lead to a significant decrease in the number of pollen grains on the stigma. For example, in previous studies, under high temperature treatment conditions, the average number of pollen grains on the stigma of the heat-resistant strain 996 was 35, while the average number of pollen grains on the thermosensitive strain 4628 was 19, indicating a significant difference between the two; Under natural conditions in the field, the average number of pollen on the stigma of the heat-resistant strain 996 is 125, while the heat sensitive strain 4628 is 132, with no significant difference between the two. Further analysis shows that the number of pollen on the stigma is determined by the cracking condition of the anthers, and there is a significant positive correlation between the two, with a correlation coefficient of 0.8476 (Zhang et al., 2008) (Figure 2).

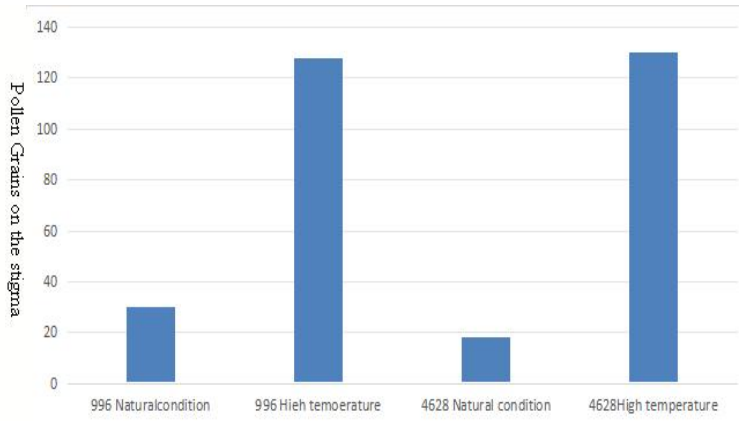

Figure 2 Effects of high temperature stress on rice pollen grains on the stigma of rice (Zhang et al., 2008)

Therefore, the impact of high temperature on the number of pollen grains on rice stigma involves complex physiological and ecological mechanisms, including pollen development and physiological adaptation of the stigma. A deeper understanding of this impact mechanism not only helps to explain the adverse effects of high temperature on rice yield, but also provides important scientific basis for the future development of high-temperature resistant varieties and the formulation of agricultural management strategies. The reduction of pollen caused by high temperature may be related to the sensitivity of pollen development and changes in the physiological state of the stigma. Under high temperature stress, pollen development may be disrupted, leading to incomplete development or early death. At the same time, the stigma is stimulated by high temperature, which may cause dehydration of the stigma cells and degeneration of the cell wall, affecting the reception and support ability of the stigma, thereby reducing the survival and attachment ability of pollen on the stigma.

This influence may also affect the fertilization process and final yield of rice. The number of pollen on the stigma is not only related to pollen release and pollination efficiency, but also directly affects the success rate of fertilization. In fact, studies have confirmed the close relationship between high temperature and the decrease in rice pollen grain count and yield.

2.3 The effect of high temperature stress on the size of rice pollen grains

High temperature stress is a common environmental stress during the growth and development of rice, which has a significant impact on the morphology, structure, and size of pollen. The size of pollen grains is directly related to their movement and deposition during pollination, so the impact of high temperature on pollen size may have a significant impact on the success of rice reproduction and yield.

Case studies have shown that under high temperature stress, the size of rice pollen grains usually changes. Under suitable temperature conditions, pollen grains usually have a relatively uniform shape and larger size, which is conducive to their stable carrying during wind or insect transmission. However, in high-temperature environments, pollen grains often exhibit a shrinking trend, sometimes even exhibiting irregular shapes. This change may be related to factors such as high-temperature induced denaturation of cell membrane lipids and inhibition of protein synthesis (Chaturvedi et al., 2021).

The study also found that changes in pollen particle size caused by high temperatures may affect the buoyancy and propagation distance of pollen. Smaller pollen grains are subject to greater air resistance in wind or insect transmission, which may lead to a reduction in their drift distance. This may affect the effective dissemination and pollination range of pollen, ultimately reducing the fertilization rate and yield of rice.

When rice is exposed to high temperature conditions, the average diameter of pollen grains significantly decreases, which is related to the decrease in protein content in pollen cells. The decrease in protein may lead to the relaxation of cell membranes and the reduction of pollen grain volume. This result suggests a direct regulatory effect of high temperature on the size of rice pollen grains.

The impact of high temperature stress on the size of rice pollen grains often involves multiple aspects of cell physiology and morphology regulation, which may have far-reaching effects on the fertilization process and yield of rice. In depth research on the regulatory mechanism of high temperature on pollen morphology and structure can help to better understand the physiological response of rice in the face of climate change, provide scientific basis for cultivating high-temperature resistant rice varieties, and maintain global food security.

3 The Effect of High Temperature on Rice Pollination

3.1 The impact of pollination success rate

High temperature stress is a major challenge in the context of global warming, which has a direct impact on the growth and reproduction of important crops such as rice. Among them, the success rate of pollination is one of the key factors affecting rice yield. The impact of high temperature on the success rate of rice pollination mainly involves two aspects. Firstly, high temperatures may directly affect the cracking process of anthers. Anther cracking is a crucial step in pollen release, and high temperature stress may lead to dehydration of anther cells and degeneration of cell membranes, preventing normal anther cracking and limiting pollen release.

Secondly, the impact of high temperature on pollen vitality is another important reason for the decrease in pollination success rate. High temperature may cause denaturation and oxidation of pollen proteins, leading to damage to the structure and function of pollen particles. This weakens the ability of pollen to spread during pollination, reducing the likelihood of binding to the stigma and fertilization.

Through case studies, we can gain a deeper understanding of the specific mechanism by which high temperatures affect the success rate of rice pollination. The spring and summer hybrid rice seed production often encounters high temperature weather during the flowering and pollination period, which has a serious impact on flowering and pollination. The basic conditions for a safe flowering and pollination period are summarized as follows: the daily average temperature is not continuously below 21 ℃ or above 35 ℃ for 3 days, and the temperature at the panicle during flowering is not continuously below 24 ℃ or above 35 ℃ for 3 days, with the most suitable temperature being 28 ℃; If the relative humidity is below 75% or above 90% for 3 consecutive days, the most suitable is 85%. However, there is a negative correlation between humidity and temperature. According to observations, the relative humidity of the ear at 35 ℃ is only 75% (Zhao et al., 2023). It indicates that the success rate of rice pollination generally decreases under high temperature conditions. Meanwhile, high temperatures may hinder anther cracking, reduce pollen vitality, and even have adverse effects on the morphology and structure of pollen particles, thereby affecting the effectiveness of pollination.

It can be seen that the impact of high temperature stress on the success rate of rice pollination is complex and multifaceted. By studying the specific mechanisms of high temperature on anther cracking and pollen vitality, we can gain a deeper understanding of the vulnerability of rice reproductive systems under high temperature stress. This helps to provide scientific basis for cultivating high-temperature resistant rice varieties to ensure the sustainability of agricultural production under constantly changing climate conditions.

3.2 Adjustment of interaction between stamens and pistils

High temperature stress has a profound impact on the reproductive system of rice, and the interaction between stamens and pistils is considered a crucial regulatory link. Through case studies, we can gain a more detailed

understanding of the regulatory mechanism of interaction between rice stamens and pistils under high temperature stress.

Research has found that high temperature stress may cause dysregulation of the interaction between rice stamens and pistils, thereby affecting the normal fertilization process. For example, some experiments have shown that when rice is subjected to high temperature stress, the pollen yield and quality of the stamens are affected, and the fertilization ability of the pistils may also be inhibited. This is because high temperature may cause dehydration of stamen cells and abnormal protein synthesis, affecting the development and release of pollen. Meanwhile, the high temperature stimulation on the pistil may lead to a decrease in its ability to accept pollen, thereby affecting the success rate of fertilization (Fan et al., 2020).

At the molecular level, the regulation of gene expression in rice stamens and pistils by high temperature is also an important research direction. Case studies have shown that under high temperature conditions, the expression of some genes related to the development of stamens and pistils is significantly altered. This includes key genes that affect pollen development and genes related to controlling pistil fertilization. These changes may lead to asynchronous signal transduction between stamens and pistils, affecting normal pollen transmission and the fertilization process of pistils (Xing et al., 2021).

In fact, some studies have also discovered the self-regulation mechanism of interaction between stamens and pistils in rice plants under high temperature stress. For example, under high temperature conditions, rice may respond to the weakening of the pistil by increasing pollen yield and improving pollen activity. This indicates that rice may maintain the relative stability of its reproductive system through certain adaptive mechanisms when facing high temperature pressure.

Overall, the adjustment of interaction between stamens and pistils in rice under high temperature stress involves multiple levels, including morphology, physiology, and molecular level. A deeper understanding of these adjustment mechanisms helps us better understand the impact of high temperature on rice reproduction and provides a theoretical basis for cultivating rice varieties that are adapted to high temperature. This is particularly urgent for ensuring global food security in the face of intensifying climate change.

3.3 High temperature stress during booting stage leads to abnormal pollen development

High temperature stress is a common agricultural meteorological disaster in the growth and development of rice, especially during the panicle stage. Its adverse effects on rice pollen development have become one of the main factors limiting high and stable yields. A study conducted an in-depth investigation into the effects of high temperature stress during the booting stage on rice pollen development, with a focus on revealing the key roles of ROS and ABA in this process.

Research has found that high temperature stress causes a significant increase in ROS (reactive oxygen species) and ABA (abscisic acid) content in the developing anther organs of rice. The increase of these two factors is not only closely related to the early degradation of anther tapetum cells and the loss of starch in pollen grains, but also directly leads to abnormal pollen development and abortion under high temperature.

In the study, it was found that ABA plays a crucial regulatory role in programmed cell death (PCD) and microspore apoptosis of anther tapetum cells under high temperature stress. ABA stimulates the production of ROS, thereby regulating the PCD of anther tapetum cells and the apoptosis of microspores, leading to the formation of pollen abortion under high temperature. This reveals the regulatory mechanism of ABA in the abnormal development of rice pollen under high temperature stress, providing new insights into the impact of high temperature on the rice reproductive system (Zheng et al., 2019) (Figure 3).

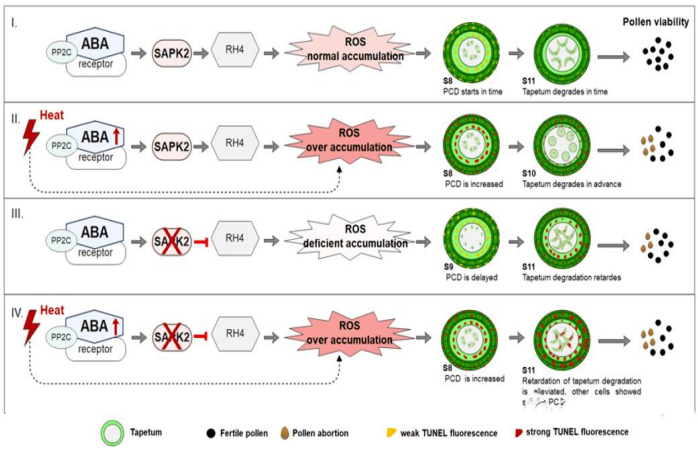

Figure 3 ABA Modulation of High-Temperature Stress on ROS Accumulation and Tapetum PCD in Rice Anther (Zhao et al., 2023)

In addition, the study also identified some key genes related to ABA signal regulation. SAPK2 and RH4 genes are involved in the regulation of high-temperature pollen fertility in rice under high temperature conditions, and they are closely related to ABA signaling and ROS oxidative damage. The interaction between these genes further reveals key regulatory sites in the production of ROS in rice floral organs and the process of PCD in the tapetal layer (Zhao et al., 2023).

This study provides new clues for exploring the relationship between ROS signals and ABA signals during the formation of high-temperature pollen abortion in rice. By revealing the molecular mechanism of abnormal pollen development in rice under high temperature stress, this study provides a useful theoretical basis for cultivating more high-temperature tolerant rice varieties and improving rice yield in the future.

4 The Molecular Mechanism of High Temperature on the Development of Rice Reproductive Organs

4.1 Changes in gene expression

High temperature stress, as a key environmental factor in rice growth and development, has a significant impact on the development of rice reproductive organs. Research has shown that high temperatures cause changes in the expression of multiple genes in rice reproductive organs, involving key tissues and processes such as anthers, female panicles, microspores, and pollen. In terms of anthers (stamens), high temperature stress causes a series of gene expression changes, including genes related to key physiological processes such as pollen development, anther cracking, and pollen release. Some genes may be negatively regulated by high temperature, leading to abnormal anther cracking and hindered pollen development. On the other hand, high temperature may induce the expression of some stress response genes, which are involved in the response of anthers to high temperature stress.

In terms of female panicles (stigma), high temperature stress has also triggered a series of gene expression changes, involving the growth and development of stigma and fertilization process. Some genes may be involved in the adaptive regulation of stigma to high temperature to maintain its normal physiological function. However, other genes may be suppressed by high temperature, affecting the fertilization efficiency of the stigma (Andr á si et al., 2021).

The gene expression changes of microspores are also an important research direction under high temperature stress. High temperature may cause abnormal development of microspores, affecting the quality of mature pollen grains. The changes in gene expression may involve physiological processes such as microspore differentiation, cell wall synthesis, and antioxidant stress. In terms of pollen, the impact of high temperature on pollen gene expression is directly related to the success rate of rice fertilization. Some genes related to pollen vitality, particle structure, and fertilization process may undergo changes under high temperature stress, leading to abnormal pollen development and reduced fertilization efficiency.

4.2 Regulation of protein synthesis and metabolism

High temperature is one of the key environmental factors affecting the growth and development of rice, and its impact on protein synthesis and metabolism has received widespread attention in practical research. By analyzing examples, we aim to gain a deeper understanding of the regulatory mechanisms of high temperature on rice protein synthesis and metabolism. A study conducted a detailed investigation into the proteomics of rice under high temperature stress during the booting stage. Under high temperature conditions, the expression levels of some key proteins in rice leaves have undergone significant changes. Among them, the expression of some heat shock proteins (HSPs) and antioxidant enzymes was significantly upregulated, reflecting the heat stress response mechanism initiated by plants to cope with high temperature. The increase of these proteins may help protect the stability of cell membranes and the normal function of organelles (Matsumura et al., 2020).

Some proteins related to photosynthesis and nitrogen metabolism have decreased expression levels under high temperature. For example, Rubisco (Ribulose-1,5-bisphosphonate carboxylase/oxygenase) is a key enzyme involved in photosynthesis, and its expression level is negatively regulated by high temperature. This may lead to a decrease in photosynthetic efficiency and affect the synthesis of photosynthetic products. In terms of protein degradation, high temperature conditions may activate proteasomes and autophagy pathways, accelerating protein degradation. Some specific proteins may be labeled as degradation targets through the ubiquitination pathway to cope with protein denaturation and instability caused by high temperature.

In addition, high temperature may also affect gene expression related to protein synthesis and metabolism by regulating transcription factors and signaling pathways. For example, high temperature may lead to the activation of some transcription factors related to heat stress, thereby regulating the expression levels of genes related to protein synthesis. Combining analysis, it is not difficult to see that the regulation of high temperature on rice protein synthesis and metabolism is a complex network, which involves multiple aspects such as heat stress response, photosynthesis, nitrogen metabolism, etc., and has a profound impact on the growth and development of rice. Deeply studying these regulatory mechanisms can provide scientific basis for cultivating rice varieties with high-temperature adaptability, ensuring the sustainability of agricultural production under constantly changing climate conditions.

4.3 Participation of hormone signaling pathways

High temperature stress has a profound impact on the hormone signaling pathways of rice, involving plant hormones such as gibberellin (GA), abscisic acid (ABA), ethylene (ET), salicylic acid (SA), etc. The following is an example analysis to gain a deeper understanding of the specific involvement and physiological response of high temperature in rice hormone signaling pathways. A study focused on the hormone regulation of rice panicles under high temperature. Under high temperature conditions, the ABA level in rice panicles significantly increases. ABA, as an important stress response hormone, may play a role in regulating physiological responses such as osmotic regulation and enhancing antioxidant capacity under high temperature stress. During this process, high temperature may induce the expression of ABA synthesis related genes, while inhibiting the expression of ABA degradation related genes, leading to the accumulation of ABA in plants (Zhong et al., 2020).

At the same time, gibberellin (GA) may exhibit opposite trends under high temperature stress. Under high temperature conditions, the level of GA in rice may decrease. GA is usually associated with promoting growth and development in plant growth and development, and high temperature stress may inhibit the biosynthesis of GA, thereby affecting the normal growth of rice plants.

In addition, ethylene (ET) is also a hormone that plays a crucial role in high-temperature response. High temperature may promote the production of more ethylene in rice, thereby participating in the adaptive response to high temperature stress. Ethylene is believed to be involved in regulating the physiological and biochemical responses of plants to stress, including increased activity of antioxidant enzymes and promotion of root growth.

Through in-depth research on the molecular mechanisms of these hormone signaling pathways, it is helpful to better understand the physiological effects of high temperature on rice and provide theoretical basis for cultivating high-temperature resistant rice varieties. This comprehensive research helps us better understand the adaptive mechanisms of plants in the face of climate change, and provides scientific basis for stress resistant breeding of food crops.

5 Outlook

High temperature stress poses significant challenges to the reproductive process of rice, especially during the pollen development and pollination stages. Under high temperature conditions, the development of rice pollen undergoes a series of complex changes, profoundly affecting the reproductive success of plants. During the breeding process, high temperatures have a profound negative impact on the development and pollination of rice pollen. The key stages of pollen development, especially microspore differentiation and pollen grain maturation, exhibit high sensitivity to high temperatures. This leads to abnormal pollen development, decreased vitality, and survival rate, directly affecting the success rate of pollination, thereby threatening rice yield and quality.

High temperature has triggered the regulation of hormone signaling pathways in rice. Hormones such as ABA, GA, and ethylene directly participate in the response mechanism of rice under high temperature stress. The increase of ABA may reflect the adaptability of plants to high temperatures, while the decrease of GA may be related to the inhibition of growth and development. The increase of ethylene under high temperature may be a defensive response, participating in physiological and biochemical regulation in adverse environments (Asad et al., 2019).

In addition, at the molecular level, high temperature has a significant impact on protein synthesis and metabolism in rice. The synthesis rate of proteins is inhibited, and the composition and stability of protein synthesis also undergo changes. This may respond to protein abnormalities caused by high temperature by activating proteasomes and other degradation pathways. In order to effectively cope with the impact of high temperature on rice, future research needs to have a deeper understanding of these molecules and physiological mechanisms. Based on these understandings, cultivating high-temperature resistant rice varieties is an urgent task. At the same time, suggestions for agricultural practice include adjusting planting structures, optimizing agricultural management, and introducing varieties that are more suitable for high-temperature environments.

Comprehensive research and comprehensive agricultural management are key to effectively mitigating the impact of high temperatures on rice, which not only helps to increase rice yield but also provides practical and feasible strategies for global food security. Secondly, in agricultural practice, measures such as improving planting structure and adjusting sowing time reasonably should be taken to adapt to high-temperature environments. Introducing rice varieties that are more tolerant to high temperatures is a crucial step, and these varieties should possess excellent characteristics such as high yield, disease resistance, and stress resistance. In addition, farmers can also reduce the negative impact of high temperature on rice growth through reasonable field management, such as avoiding cultivation during peak periods of high temperature, scientific fertilization, and irrigation.

In terms of technological innovation, agricultural technology can play a crucial role. We should strengthen research on genetic improvement of rice under high temperature, and use techniques such as gene editing to cultivate rice varieties that are more tolerant to high temperature. At the same time, develop efficient agricultural management software and decision support systems to help farmers better cope with meteorological changes, optimize production plans, and improve the adaptability of agricultural production. Future research and agricultural practices should adopt multi-level and multifaceted strategies to address the impact of high temperatures. Through scientific research and innovative agricultural practices, we can better adapt to climate change and ensure global food security.

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