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[Review Paper]

Climate change impacts on wheat production: Reviewing challenges and adaptation strategies

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Abstract

This article delves into the multifaceted impacts of climate change on wheat production. Firstly, it provides a detailed analysis of the direct and indirect effects of temperature changes on wheat growth, including the potential impacts of warm seasons and extreme temperature events on the lifecycle, growth rate, and quality of wheat. Secondly, the article examines changes in precipitation patterns, discussing the potential effects of droughts and floods on wheat yield and water stress. Against the backdrop of rising carbon dioxide concentrations in the atmosphere, the article thoroughly investigates the potential impacts of CO2 concentration on wheat growth, nutrient absorption, and quality. Additionally, the challenges posed by rising sea levels to wheat cultivation in coastal areas, especially the issues related to saltwater intrusion, are highlighted. The article also extensively discusses the selection of wheat varieties and genetic adaptability, as well as agricultural practices to address climate change. This article aims to provide insights into ensuring the future sustainability and resilience of wheat agriculture.

Keywords

climate change impacts, wheat production challenges, adaptation strategies, wheat growth, wheat production

1. Introduction

Climate change has widespread and profound impacts on global agriculture. The rise in global temperatures has led to changes in climate patterns, including more frequent extreme weather events, irregular precipitation, and prolonged warm seasons. These changes directly affect agricultural production, increasing the frequency of extreme weather events such as droughts, floods, and storms. Furthermore, climate change has caused sea level rise, glacier melting, and ecosystem changes, creating various pressures on global agriculture.

Within global agriculture, wheat holds a unique and crucial position. As a major staple crop, wheat provides essential food and energy sources for people worldwide. However, the growth and development of wheat are highly dependent on the stability of climate conditions. The rising temperatures and irregular precipitation patterns may lead to fluctuations in wheat yield, thereby impacting the global food supply chain. The special status of wheat underscores the urgency of in-depth research on the effects of climate change to

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ensure global food security and the sustainability of agriculture [1-3].

As a primary global staple crop, the impact of climate change on wheat manifests as a demand for adaptability to its growth environment and stability in quality. To maintain high yields and quality of wheat, agricultural scientists are actively researching adaptive agricultural practices, selecting more drought-resistant and heat-tolerant wheat varieties, and promoting sustainable agricultural development. These efforts aim to address the challenges posed by climate change to wheat production, ensuring that the global agricultural system can adapt to new climate conditions and maintain the stability of the food supply [4,5].

This article thoroughly investigates the multifaceted impacts of climate change on wheat production, to enhance the sustainability and adaptability of wheat agriculture. Firstly, the article focuses on the direct and indirect effects of temperature changes on wheat, exploring the potential impacts of warm seasons and extreme temperature events on the wheat lifecycle, growth rate, and quality. Secondly, the article examines changes in precipitation patterns, investigating the potential effects of droughts and floods on wheat yield and water stress. In the context of rising carbon dioxide concentrations in the atmosphere, the article delves into the potential impacts of CO2 concentration on wheat growth, nutrient absorption, and quality. Additionally, the article addresses the challenges posed by sea level rise to wheat cultivation in coastal areas, with a specific focus on potential issues arising from saltwater intrusion. The article also discusses in-depth the selection of wheat varieties and genetic adaptability, as well as adjustments in agricultural practices to enhance wheat's adaptability to climate change.

2. Effect of temperature change on wheat

2.1. Impact of warm seasons

The influence of warm seasons on wheat production is a crucial aspect of climate change [6-10]. Firstly, with the global rise in temperatures, an extension and intensification of warm seasons have become a prevailing trend, directly affecting the growth cycle of wheat. Elevated temperatures may lead to an advancement of the growing season in wheat cultivation areas, accelerating the reproductive process, and thereby impacting the growth stages and production cycles of wheat. Additionally, warm seasons may increase the evaporation of moisture from the soil, leading to soil dryness and posing challenges to the water supply for wheat.

Secondly, the impact of warm seasons on the quality of wheat is also a matter of concern. Warm seasons can accelerate the formation of wheat grains, affecting the accumulation of starch and proteins, and thereby influencing the quality characteristics of wheat. The decline in wheat quality may manifest as inferior gluten properties, and weakened bread fermentation capabilities, affecting both the edible value and the quality requirements for industrial processing.

Moreover, warm seasons may contribute to issues related to pests and diseases during wheat growth. Favorable climatic conditions created by warm temperatures may accelerate the reproduction rates of certain

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pathogens and pests, increasing the risk of wheat crops being affected by diseases and pest infestations. This poses a potential threat to both the yield and quality of wheat.

2.2. Impact of extreme temperature events

Extreme temperature events pose significant challenges to wheat production and represent a key aspect triggered by climate change [11-15]. Firstly, extreme high-temperature events can increase stress on wheat growth. High temperatures accelerate evaporation, leading to soil dryness and impacting the growth rate and reproductive processes of wheat. Simultaneously, extremely high temperatures may directly affect the photosynthesis of wheat, reducing the plant's efficiency in utilizing solar energy, and thereby influencing nutrient absorption and grain formation.

Secondly, extremely high temperatures also have adverse effects on the yield and quality of wheat. Under high temperatures, wheat may experience phenomena such as another abscission and reduced pollen vitality, resulting in a decrease in pollen quantity and pollination rate, ultimately affecting grain formation. This could lead to a reduction in wheat yield. Additionally, as high temperatures can affect the synthesis of starch and proteins, the quality of wheat may also be compromised, manifesting as weakened gluten strength and overall quality decline. Extreme low-temperature events similarly impact wheat. Cold temperatures may lead to frost and freezing, causing direct harm to wheat seedlings and mature plants. Low temperatures may also result in slow wheat growth, and delayed reproductive processes, thereby affecting both yield and quality.

Moreover, extreme temperature events present challenges in the control of pests and diseases affecting wheat. Some pathogens and pests may proliferate rapidly in warm environments, and under extremely high or low temperatures, wheat may become more vulnerable, making it more susceptible to disease and pest infestations.

2.3 Chilling requirement and wheat quality

The chilling requirement refers to the need for low-temperature conditions during the growth and development of wheat, and it holds significant importance in the formation and maintenance of wheat quality[16-20]. Firstly, low-temperature conditions are crucial for the reproductive growth phase of wheat, particularly during the flowering period. Moderate low temperatures help stimulate the formation and germination of wheat pollen, enhancing pollination rates and, consequently, influencing grain formation. Suitable low-temperature conditions also contribute to slowing down the growth rate of plants, enabling them to better adapt to the ecological environment, resulting in robust stem development and a stable spike structure.

Secondly, the impact of low-temperature conditions on wheat quality is primarily manifested in the synthesis and accumulation of starch and proteins. Moderate low temperatures contribute to increasing the starch content in wheat grains, improving the crystallinity of starch, and thereby affecting the quality of

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wheat gluten. Additionally, low temperatures promote the synthesis of proteins in wheat plants, enhancing the protein content in flour. This is beneficial for improving the strength and elasticity of wheat dough, crucial for the production of excellent pastries and noodles.

On the other hand, prolonged exposure to high-temperature environments may lead to the occurrence of “heat damage” in wheat, characterized by starch gelatinization and protein denaturation. This affects the processing and quality characteristics of wheat flour. Therefore, suitable low-temperature conditions are necessary during the wheat growth process, especially during critical reproductive stages such as jointing, heading, and grain-filling periods.

3. Effect of precipitation pattern change on wheat

3.1 Impact of drought on wheat

Drought poses a major challenge to wheat production, exerting profound effects on its growth, yield, and quality [21-25]. Firstly, drought directly influences the growth and developmental processes of wheat. As water is a vital factor for wheat growth, insufficient water availability during the reproductive stage can stress plants, impacting stem elongation and leaf expansion, subsequently affecting photosynthesis and nutrient absorption. This may lead to reduced wheat yield and delayed growth of plants.

Secondly, the impact of drought on wheat yield is particularly significant. Water scarcity can result in poor development of wheat spikes, affecting pollen production and dissemination, reducing pollination rates, and thereby inhibiting grain formation. This directly and negatively affects wheat yield and the economic output of farmland, increasing risks faced by farmers.

On the other hand, drought also affects the quality of wheat. Insufficient moisture can lead to a decrease in the accumulation of starch and proteins in wheat grains, affecting dough stickiness and elasticity. Quality deterioration impacts the taste and processing characteristics of wheat products, negatively affecting the food industry and pastry production.

Under drought conditions, wheat is more susceptible to pest and disease attacks. Due to the lack of sufficient water, the plant’s resistance to diseases weakens, making wheat more prone to infections by fungi, bacteria, and pests, thereby increasing the difficulty of agricultural management. To counter the adverse effects of drought on wheat, agricultural research and practices have adopted a range of water resource management strategies, including water-saving irrigation, the development of drought-resistant varieties, soil improvement, and drought-tolerant agricultural practices. These measures aim to enhance wheat plants’ adaptability to drought, maintaining the stability and sustainability of wheat production. Against the backdrop of climate change, in-depth research on the impact of drought on wheat and the urgent development of innovative solutions have become increasingly crucial.

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3.2. Impact of extreme rainfall and flood events on wheat

The effects of extreme rainfall and flood events on wheat production are complex and multifaceted [26-30]. Firstly, extreme rainfall can lead to excessive soil moisture, increasing the risk of damage to wheat roots. Prolonged soil saturation can lead to root hypoxia, affecting the plant's ability to absorb water and nutrients, thereby impacting the growth and development of wheat. Moreover, excess water may cause root rot and the dissolution of heavy metals in the soil, creating adverse conditions for wheat growth.

Secondly, flood events may result in waterlogging in wheat fields, causing direct mechanical damage to wheat plants. Excessive water can lead to lodging and breakage of plants, affecting normal growth and fruiting of wheat. Additionally, floods may wash away nutrients from the soil, causing nutrient deficiencies in wheat plants, and subsequently affecting yield and quality. After flooding, the dilution of nitrogen in the soil may lead to nitrogen deficiency in wheat. Nitrogen is a crucial nutrient essential for wheat growth, playing a vital role in nutrient absorption and protein synthesis. Therefore, flood events may subject wheat plants to nutrient limitations, affecting the development and quality characteristics of wheat.

Furthermore, floods may release harmful substances into the soil, such as heavy metals and pesticide residues, posing potential contamination risks to wheat. This poses a threat to the quality and edible safety of wheat and agricultural products, causing negative impacts on agricultural production and markets. To mitigate the adverse effects of extreme rainfall and flood events on wheat, agricultural practices include improving drainage systems, selecting wheat varieties with greater adaptability, and adjusting planting periods to avoid peak rainfall periods. These strategies help enhance wheat resistance to extreme rainfall and floods, maintaining the sustainability and stability of wheat production. In the context of climate change, in-depth research and the development of innovative solutions for these issues become particularly crucial.

3.3. Water stress and yield loss in wheat production

Water stress is one of the most significant ecological factors in wheat production, exerting profound and direct impacts on wheat yield [31-35]. Firstly, water stress leads to insufficient water supply in the soil, directly affecting the growth and development of wheat. During critical growth stages, such as heading and grain filling, water deficiency may result in a significant reduction in wheat yield. Under drought conditions, wheat plants may experience water stress, leading to poor stem development, leaf curling, leaf shedding, and physiological responses that ultimately affect the formation and development of wheat spikes.

Secondly, the impact of water stress on wheat yield involves the development and dissemination of pollen. Under water stress conditions, pollen formation and development are inhibited, affecting wheat pollination rates. The reduction in pollination rates directly leads to a decrease in wheat grain production, subsequently reducing overall wheat yield.

On the other hand, water stress may also limit nutrient absorption in wheat plants. Insufficient water affects nutrient dissolution in the soil and nutrient absorption in plants, especially critical nutrients such as nitrogen, phosphorus, and potassium. This results in hindered growth of wheat plants, impacting plant morphology and development processes, ultimately reducing wheat yield. Under water stress conditions, physiological and metabolic changes occur in wheat, potentially leading to a decline in quality. Water stress may affect the synthesis of starch and proteins in wheat grains, influencing gluten strength and the processing quality of wheat dough, diminishing the commercial value of wheat.

To mitigate the impact of water stress on wheat yield, agricultural practices include rational irrigation management, the selection of more drought-resistant wheat varieties, and improvements in soil water retention capabilities. These measures contribute to enhancing wheat resistance to water stress and maintaining the stability and sustainability of wheat production. Given the challenges posed by climate change and the increasing pressure on water resources, in-depth research on the relationship between water stress and wheat yield becomes particularly important.

4. Effect of carbon dioxide concentration

4.1. Changes in atmospheric carbon dioxide concentration

The variation in atmospheric CO2 concentration is a crucial environmental factor in the climate system, exerting widespread impacts on wheat production and global agriculture [36-40]. Firstly, human activities such as industrial processes, fossil fuel combustion, and changes in land use have led to a gradual increase in atmospheric CO2 concentration. This heightened concentration enhances the greenhouse effect, causing an elevation in Earth's surface temperature and subsequently triggering climate change.

In wheat production, the elevated CO2 concentration has direct and indirect effects on wheat growth, nutrient absorption, and quality. Firstly, high concentrations of CO2 serve as a carbon source, promoting photosynthesis and enhancing the growth rate of wheat. This may lead to increased biomass accumulation in wheat plants within the same timeframe, ultimately boosting yield. However, this may also induce changes in nutrient absorption and distribution, impacting the quality of wheat.

Secondly, the elevated CO2 concentration may result in alterations in starch and protein content in wheat. While the increased CO2 concentration can stimulate starch synthesis, it may simultaneously reduce the protein content in wheat. This has the potential to affect gluten strength and quality characteristics of wheat, presenting challenges for wheat processing and its nutritional value.

On the other hand, the rise in CO2 concentration may interact with elevated temperatures, triggering complex effects of climate change. This includes more frequent extreme weather events and changes in precipitation patterns, introducing uncertainties and challenges to wheat production. To better understand the impact of changes in CO2 concentration on wheat, scientists utilize methods such as greenhouse gas experiments and climate model simulations. This helps predict potential changes in wheat production under future climate conditions and provides a scientific basis for adopting adaptive agricultural practices and breeding varieties. In the global effort to mitigate climate change, monitoring changes in atmospheric CO2

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concentration is crucial for ensuring the sustainable production of wheat and other cereal crops.

4.2. Relationship between wheat growth and carbon dioxide concentration

There is a close relationship between wheat growth and atmospheric CO2 concentration, as CO2 is a key substance for photosynthesis. With the rise in atmospheric CO2 concentration over recent centuries due to human activities, scientific research has increasingly focused on the impact of CO2 on wheat growth [41-45].

Firstly, elevated CO2 concentrations can enhance wheat photosynthesis. In photosynthesis, plants absorb CO2, light energy, and water, producing oxygen and synthesizing organic compounds. Therefore, increasing atmospheric CO2 concentration helps supply more carbon to wheat, promoting photosynthesis and enhancing the growth rate of plants.

Secondly, high CO2 concentrations affect the reproductive stages of wheat. Some studies suggest that higher CO2 concentrations may shorten the reproductive cycle of wheat, causing it to enter the heading and grain-filling stages earlier. This may lead to a faster transition of wheat plants to the reproductive growth stage, affecting the development of spikes and the formation of grains.

However, although high CO2 concentration promotes wheat growth, it may also trigger some issues. One of these issues is an imbalance in nutrient absorption. In a high CO2 environment, plants may excessively rely on the rate of photosynthesis, leading to uneven nutrient absorption and distribution, impacting the quality of wheat.

On the other hand, high CO2 concentration induces changes in wheat's stress resistance. Some studies suggest that elevated CO2 levels may increase wheat's tolerance to climate change, drought, and pest infestations to a certain extent.

4.3. Impact on nutrition and quality

The growth environment of wheat, including soil nutrients, water, temperature, and other factors, directly influences its quality and nutritional value. The following are the main effects of these factors on the nutrition and quality of wheat [46-50].

1) Soil nutrients. Soil nutrient content significantly influences wheat growth. Elements such as nitrogen, phosphorus, and potassium are essential nutrients for wheat. Adequate nitrogen contributes to increased growth rate and yield, affecting gluten and protein content. Phosphorus and potassium are crucial for wheat's developmental stages and spike formation. Nutrient deficiencies may result in slow wheat growth, decreased yield, and impact wheat quality.

2) Water. Appropriate water levels are crucial for wheat growth. Water stress can lead to reduced stem and leaf development, affecting photosynthesis and nutrient absorption. Insufficient water can also reduce the synthesis of starch and protein, impacting wheat gluten strength and quality.

3) Temperature. Temperature significantly affects wheat growth rate, developmental stages, and quality.

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Warmer seasons may lead to an accelerated growth cycle, but can also influence wheat quality characteristics. Extreme temperature events, such as high and low temperatures, may result in reduced yield and quality, affecting adaptability and resilience.

4) Carbon dioxide concentration. Increased atmospheric carbon dioxide concentration may enhance photosynthesis and growth rates in wheat. However, this could lead to an imbalance in nutrient absorption, affecting wheat quality.

5) Pests and diseases. Wheat quality and nutrition are directly threatened by pests and diseases. Pathogens and pests can reduce wheat yield and impact its chemical composition, negatively affecting flour quality.

To maintain wheat quality and enhance its nutritional value, various management practices are implemented in agriculture, including appropriate fertilization, irrigation management, and pest control. Additionally, breeding resilient and disease-resistant wheat varieties is a crucial approach to improving wheat quality and nutrition, thereby increasing the sustainability of wheat production.

5. Sea level rise and challenges of wheat cultivation in coastal areas

5.1. Sea level rise in coastal areas

Sea level rise in coastal areas is a significant phenomenon caused by climate change, exerting extensive and profound impacts on the ecosystems, societies, and economies of these regions. The following are the primary effects of sea level rise on coastal areas [51-55].

1) Coastal erosion. Sea level rise results in the inland movement of coastlines, triggering coastal erosion. Coastal areas, including beaches, coastal vegetation, and ecosystems, are damaged, posing potential threats to coastal communities, ports, and infrastructure. This can lead to the endangerment of houses, roads, and other infrastructure, increasing the disaster risk for coastal communities.

2) Saltwater intrusion. Sea level rise may lead to the intrusion of saltwater into coastal groundwater and soil, affecting local freshwater resources. This poses a threat to agriculture and freshwater supplies, particularly in low-lying areas. Saltwater intrusion can also harm plants and ecosystems, impacting local biodiversity.

3) Increased flooding risk. Sea level rise increases the risk of flooding in coastal areas. Tides and storm surges can more easily breach seawalls and other protective structures, leading to inland flooding. This presents greater natural disaster risks for low-lying coastal plains and coastal cities, affecting people's lives and property.

4) Ecosystem changes. Sea level rise directly and indirectly impacts coastal ecosystems. Coastal wetlands, marshes, coral reefs, and other ecosystems may face destruction, affecting the habitats of fish and other wildlife. This has negative implications for coastal economic activities such as fisheries and tourism.

5) Socioeconomic impacts. The disasters and ecosystem changes triggered by sea level rise have profound social and economic impacts on coastal communities. Land and property loss, population migration,

unemployment, and social instability are potential outcomes. Sea level rise also increases the costs of maintaining and rebuilding coastal infrastructure, posing economic challenges to local governments and residents.

To address the challenges of sea level rise, measures include strengthening coastal defenses, raising construction standards for coastal cities, implementing climate change adaptation policies, and promoting the protection and restoration of ecosystems. International cooperation is essential to collectively address coastal issues arising from climate change.

5.2. Adverse effects of saltwater intrusion on wheat growth

Saltwater intrusion refers to the infiltration of seawater or saline water into land or water sources that were originally freshwater, causing severe adverse effects on the growth of wheat. The following provides a detailed explanation of the impacts of saltwater intrusion on wheat [56-60].

1) Water stress. Upon the entry of salt into the soil, it affects soil water absorption and the water uptake by plant roots. High soil salinity leads to water stress for wheat plants, as it hinders the movement of water between the soil and plants, directly affecting the normal growth and development of wheat.

2) Ionic imbalance. Saltwater intrusion increases the salt concentration in the soil, causing an imbalance in soil ions. Excessive salts, particularly chloride and sodium ions, hinder the wheat roots' absorption of water and other essential nutrients such as nitrogen, phosphorus, and potassium. This affects wheat's nutrient absorption and plant metabolic processes.

3) Physiological damage. High soil salinity induces physiological damage to wheat plants, including damaged cell membranes, leaf margin scorching, leaf yellowing, and leaf shedding. These physiological damages not only slow down the growth rate of wheat but also reduce its resilience, making it more susceptible to other environmental pressures.

4) Impact on yield and quality. Saltwater intrusion directly influences the yield and quality of wheat. Salt stress leads to reduced wheat yields as plants struggle to grow and develop normally. Additionally, salt content may affect wheat quality characteristics such as gluten strength, starch, and protein content, thereby diminishing the commercial and edible value of wheat.

5) Soil degradation. Prolonged saltwater intrusion results in the accumulation of salts in the soil, accelerating soil degradation. This poses a long-term threat to the continuous production of wheat and other crops since highly saline soils are challenging to restore to a state conducive to plant growth.

To mitigate the adverse effects of saltwater intrusion on wheat, agricultural practices include measures such as improving saline-alkali land, implementing sensible irrigation management, breeding salt-tolerant wheat varieties, and enhancing soil drainage systems. These strategies contribute to enhancing wheat's adaptability to salt stress and maintaining the sustainability of wheat production.

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5.3. Challenges in wheat cultivation in humid environments

Cultivating wheat in humid environments presents a series of challenges and issues, encompassing aspects such as soil management, pest and disease control, and quality preservation. The following outlines the primary challenges faced in wheat cultivation in humid environments [61-65].

1) Moisture management. Humid environments typically entail high humidity and frequent rainfall, posing difficulties in moisture management for wheat growth. Excessive moisture may lead to overly wet soil, affecting the gas exchange and water absorption of wheat roots, and potentially causing root rot. Conversely, poor drainage may result in water retention, increasing the risk of water stress. Therefore, achieving proper moisture management is a key challenge in humid environments.

2) Diseases and fungal infections. High humidity provides ideal conditions for the growth and proliferation of fungi and pathogens, increasing the risk of wheat diseases. Common diseases include powdery mildew, Fusarium head blight, and rust, causing damage to wheat leaves, stems, and spikes, impacting growth, development, and reducing yields. Effectively combating these diseases requires implementing measures such as selecting disease-resistant wheat varieties and regular fungicide spraying.

3) Quality and processing Issues. Humid environments may result in excessive moisture content in wheat grains, affecting the quality and processing characteristics of wheat. High moisture content makes wheat more susceptible to mold and fungi, while also complicating storage and processing. This poses a direct threat to the flour quality and edible value of wheat.

4) Soil quality decline. In humid environments, the soil is prone to waterlogging and salt accumulation, leading to a decline in soil quality. This can cause soil acidification, nutrient loss, and structural damage, negatively impacting wheat growth. Maintaining soil quality and implementing effective soil improvement measures are crucial for wheat cultivation in humid environments.

5) High temperatures and extreme weather events. Humid environments often come with high temperatures and extreme weather events such as heatwaves and heavy rainfall. These factors may result in the instability of wheat growth stages, affecting critical phases like heading and grain filling, subsequently influencing yield and quality.

To overcome these challenges, comprehensive management strategies in agricultural practices are necessary. These include selecting wheat varieties with strong adaptability, implementing effective moisture management, regular pest and disease control, improving soil quality, and adjusting planting schedules. In the context of climate change, in-depth research and innovative solutions to the challenges of wheat cultivation in humid environments become particularly important.

6. Selection and genetic adaptability of wheat varieties

6.1. Climate-adaptive wheat varieties

The breeding of climate-adaptive wheat varieties aims to enhance wheat’s ability to thrive, develop, and maintain high yields and quality characteristics under new climatic conditions. Addressing these aspects, the cultivation of climate-adaptive wheat varieties is a comprehensive endeavor that requires collaborative efforts among agricultural scientists, geneticists, and breeding experts to ensure the stability and sustainability of wheat production amid changing climate conditions. The following provides a detailed overview of the main features and breeding methods for climate-adaptive wheat varieties [66-70].

1) Stress tolerance. Climate-adaptive wheat varieties should exhibit strong stress tolerance, including resilience to adverse environmental conditions such as high temperatures, drought, salinity, and water stress. This involves enhancing wheat's resistance to environmental stressors to ensure stable yields when facing extreme weather events induced by climate change.

2) Disease and pest resistance. Climate-adaptive wheat varieties need to possess characteristics of disease and pest resistance, as climate change may lead to the emergence of new diseases and pests or exacerbate existing issues. Cultivating wheat varieties with robust resistance helps mitigate losses caused by diseases and pests in agricultural production.

3) Growth period regulation. Addressing the instability of growth periods caused by climate change, adapting wheat varieties to different growing seasons becomes crucial. This includes shortening or lengthening growth periods to accommodate new temperature and precipitation conditions, ensuring that wheat completes key growth and development stages at the most favorable times.

4) High yield and quality. Climate-adaptive wheat varieties must maintain high yields and excellent quality. Quality attributes such as protein content, starch composition, and gluten strength, among others, remain essential factors to consider in the breeding process. High-quality wheat varieties are more valuable for processing and consumption.

5) Water use efficiency. Under conditions of drought and water stress triggered by climate change, climate-adaptive wheat varieties should demonstrate high water use efficiency. This implies that wheat can effectively utilize limited water resources to sustain normal growth and development.

6) Genetic diversity. Emphasizing genetic diversity is crucial in enhancing wheat adaptability and resilience. Selecting parent materials with different genetic traits can improve the adaptability of the wheat population to various environmental conditions.

7) Gene editing and molecular breeding. Utilizing modern biotechnological tools such as gene editing and molecular marker-assisted breeding allows for more precise selection and improvement of wheat genes. This accelerates the breeding process, enabling wheat to adapt more rapidly to the pressures of climate change.

6.2. Gene editing and utilization of genetic resources

Gene editing and the utilization of genetic resources are crucial approaches to enhance wheat's resilience, adaptability, and yield, especially in the face of challenges posed by climate change. By comprehensively employing gene editing and genetic resources, wheat varieties better suited to climate change can be cultivated, improving their yield, resistance, and quality. This ensures a stable supply of food production in the continually changing environment. The following provides detailed explanations regarding gene editing and the utilization of genetic resources [71-75].

1) Collection and preservation of genetic resources. Genetic resources refer to the genetic diversity of plants, which is crucial for breeding wheat varieties adapted to climate change. Scientists collect and preserve different varieties and wild relatives of wheat globally, establishing genetic resource banks to ensure sufficient genetic diversity for utilization.

2) Genomics and molecular marker techniques. Using genomics and molecular marker techniques, scientists can precisely identify genes related to adaptability, disease resistance, and stress tolerance. This deepens the understanding of wheat genetic information, aiding in the accurate selection and improvement of specific genes.

3) Gene editing technology. Gene editing technologies such as CRISPR-Cas9 enable scientists to directly modify wheat genes to achieve improvements in specific traits. This technology provides higher precision and efficiency, accelerating the breeding process and allowing wheat to adapt more rapidly to new climate conditions.

4) Introduction of stress-tolerant genes. Through gene editing, scientists can introduce genes with stronger stress tolerance from other plants or wild wheat varieties into major cultivated varieties. This enhances wheat's adaptability to adverse conditions such as high temperatures, drought, and salinity.

5) Integration of disease-resistance genes. Utilizing disease-resistant genes present in genetic resources, scientists can integrate these genes into cultivated wheat varieties through gene editing or traditional breeding methods, enhancing their resistance to diseases.

6) Optimization of growth period regulation genes. Adapting to climate change, especially changing growth periods, requires the optimization of genes regulating wheat's growth periods. Understanding and adjusting these genes can help wheat better adapt to changing climate conditions.

7) Engagement with farmers and communities. Ensuring that gene-edited wheat varieties meet the needs of farmers and communities requires widespread engagement. Collaboration with local farmers helps understand their requirements and preferences for wheat varieties, ensuring that new varieties not only adapt to the environment but also align with local agricultural practices and market demands.

6.3. Adjustments in agricultural practices

Adjusting agricultural practices is crucial for adapting to climate change, enhancing agricultural sustainability, and increasing crop productivity. This requires multifaceted efforts, including technological innovation, scientific research, policy support, and community collaboration. These adjustments will help ensure that agricultural systems remain stable, sustainable, and resilient in the face of continually changing

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climate conditions. The following provides detailed explanations of adjustments in agricultural practices [76-80].

1) Improvement of tillage systems. In the process of adapting to climate change, farmers can adopt more flexible and adaptive tillage systems. This includes selecting appropriate tillage depths, adjusting planting times, and implementing soil and water conservation practices such as conservation tillage and vegetation cover to slow down water evaporation and soil erosion.

2) Water resource management. Faced with irregular rainfall and frequent droughts caused by climate change, agricultural practices need to adjust for more effective water resource management. This involves adopting water-saving irrigation techniques, optimizing irrigation and drainage systems, and collecting/storing rainwater to ensure plants receive sufficient moisture during critical growth periods.

3) Crop selection and rotation. Considering changing climate conditions, farmers can adjust crop selection and rotation plans. Choosing crop varieties adapted to local climates or introducing new crop varieties helps mitigate risks associated with climate change. Additionally, scientific crop rotation plans contribute to improving soil nutrient structure and reducing the occurrence of pests and diseases.

4) Strategies for pest and disease control. With changes in temperature and humidity, agricultural practices need to adjust pest and disease control strategies. This may include adopting biological control methods, introducing natural predators, and judicious use of pesticides to protect crops from infestations.

5) Fertilizer management. Farmers can adjust the type, timing, and quantity of fertilizer application based on changes in climate conditions. Proper fertilizer management helps improve crop yield and quality while minimizing negative environmental impacts.

6) Adoption of new technologies. Agricultural practices need to actively adopt new technologies such as precision agriculture, remote sensing, machine learning, and more. These technologies provide real-time data and precise management tools to help farmers better understand and respond to the impacts of climate change.

7) Protection of agricultural ecosystems. To maintain the ecological balance of agriculture, emphasis should be placed on protecting agricultural ecosystems. This involves proper management of farmland and surrounding ecological environments, promoting coordinated development between agriculture and natural ecosystems, and enhancing the overall stability of the ecosystem.

8) Community engagement and agricultural education. Through community engagement and agricultural education, agricultural practices can better disseminate best practices for adapting to climate change. Farmers can adapt to new environmental conditions through knowledge sharing, training, and cooperative societies.

7. Conclusions

Wheat agriculture faces a series of major challenges, including climate change, water resource

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management, soil quality, and pest pressures. These challenges pose threats to the sustainability of wheat production and global food supply. Developing effective mitigation measures is crucial at both scientific and policy levels.

Firstly, climate change has direct and indirect impacts on wheat yield and quality. Rising temperatures, irregular precipitation, and extreme weather events may lead to changes in the wheat growth cycle, water stress, and increased risks of pest and disease spread. Scientifically, in-depth research into the resistance and adaptability of wheat varieties is necessary to cultivate new varieties that are more drought-resistant, heat-tolerant, and pest-resistant. On the policy front, global climate change agreements and national-level policymaking are essential for mitigating the impact of climate change.

Secondly, water resource management is another significant challenge in wheat agriculture. Climate change increases the uncertainty of water resources, and irrational irrigation and water management may result in soil erosion and declining groundwater levels. Scientifically, the introduction of advanced irrigation techniques, improvement of water use efficiency, and the implementation of sustainable water resource management measures are needed. On the policy side, encouraging policies and regulations for sustainable water use in agriculture is crucial to ensuring fair and equitable water resource allocation among different sectors.

Additionally, declining soil quality is also a challenge in wheat agriculture. Overuse of fertilizers and pesticides, along with improper land management, leads to soil depletion and pollution, negatively affecting wheat growth. Scientifically, research promoting sustainable soil management and improvement, as well as the promotion of organic farming and crop rotation, is necessary. At the policy level, the formulation of soil health policies and the encouragement of farmers to adopt sustainable soil management practices are crucial for maintaining soil health.

Finally, as wheat agriculture faces future challenges, emphasis should be placed on research and the development of new technological innovations. This includes utilizing genetic engineering, advanced agricultural technologies, and digital agriculture to increase wheat yield and quality, enhancing agricultural resilience. In policymaking, supporting research and application of agricultural technology, encouraging the digitization of agriculture, and incorporating technological innovation into national agricultural development strategies are vital.

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