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MODERN APPROACHES TO ENHANCING RUST RESISTANCE IN WHEAT LEADING TO GLOBAL FOOD SECURITY

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ABSTRACT

Rust diseases pose significant threats to wheat production. The deployment of wheat cultivars endowed with rust resistance stands as the most potent strategy for effective rust management. This resistance is primarily inherited through Mendelian principles discovered in 1905, but traditional breeding methods are time-consuming. Modern strategies have emerged to develop rust-resistant wheat varieties efficiently. Marker-Assisted Selection (MAS) accelerates the breeding process through precise screening, bringing about a revolution in the creation of rust-resistant wheat varieties. Genetic engineering techniques allow the transfer of resistance genes from other species into susceptible crops, but GMO use remains controversial and regulated. Gene editing, especially with CRISPR-Cas9, is a game-changer, enabling the introduction of natural variations or inactivation of critical genes in rust pathogens, enhancing plant resistance. RNA interference (RNAi) is another promising strategy, using small RNA molecules to inhibit rust pathogen gene expression, reducing disease severity. Induced Systemic Resistance (ISR) primes plant immune systems by treating them with beneficial microorganisms or compounds, fortifying them against subsequent rust infections. Eco-friendly biofungicides with antagonistic microorganisms suppress rust infections as alternatives to chemical fungicides. The development of climate-resilient wheat varieties is essential, as they indirectly enhance rust resistance, ensuring stable production amid changing climate conditions. These efforts to improve wheat productivity and rust resistance are crucial for feeding the growing global population. Integrating modern methods with traditional breeding is key to effectively combatting rust diseases and enhancing food security.

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INTRODUCTION

Wheat is one of the most important staple crops and plays a significant role in ensuring food security for a large portion of the world's population (Acevedo et al., 2018). It is a major source of calories and essential nutrients, such as carbohydrates, proteins, and dietary fibers, which are crucial for human health and nutrition (Pandey et al., 2020). Wheat is adaptable to various environmental conditions (Austin, 1989), making it a valuable crop for regions with unpredictable climates or challenging growing conditions. The size of the wheat genome was estimated to be around 16.9 billion base pairs or approximately 17 GB. This makes it significantly larger than the human genome (Keller et al., 2005). Continuous research and development efforts in wheat breeding and genetics lead to improved varieties with higher yields, better disease resistance, and enhanced nutritional content, thus contributing to increased food security (Borlaug, 2007). Given its significance in global food security, efforts to improve wheat production, disease resistance, and nutritional quality continue through modern breeding techniques, research, and sustainable agricultural practices. This focus on enhancing wheat productivity and resilience is crucial in meeting the food demands of a growing global population, especially in the face of climate change and other challenges (Ober et al., 2021).

Rust in wheat refers to a group of fungal diseases caused by different species of rust fungi belonging to the genus *Puccinia*, are significant threats to wheat production worldwide and can lead to substantial yield losses if not managed properly (McIntosh et al., 1995; Mohanan, 2010). There are three main types of rust diseases that affect wheat. Leaf rust is the most common and economically important rust disease of wheat. It affects the leaves of the plant, causing small, reddish-brown, powdery pustules on the leaf surface. These pustules release thousands of spores, which can easily spread and infect other wheat plants. Severe leaf rust infections can lead to reduced photosynthesis, premature senescence, and a decrease in grain fill, ultimately leading to lower yields (Ijaz et al., 2023). Stem rust was historically one of the most devastating diseases of wheat (Afzal et al., 2021). It affects the stem and other above-ground parts of the plant. The characteristic symptom of stem rust is the appearance of reddish-brown, elongated pustules on the stems, leaves, and glumes of the wheat spike. Severe infections can cause stem breakage and lead to complete yield loss (Afzal et al., 2015). Stripe rust is also known as yellow rust due to the appearance of yellowish-orange pustules on the leaves. It is a significant threat in cooler regions and at higher elevations. Stripe rust can cause significant yield losses, especially when favorable environmental conditions favor rapid disease development (Afzal et al., 2022a, b).

Management of rust diseases in wheat involves a combination of cultural practices (Figueroa et al., 2018), chemical control (Afzal et al., 2020; Carmona et al., 2020), and genetic resistance (Afzal et al., 2018; 2022a). Planting rust-resistant wheat varieties is one of the most effective and sustainable approaches to managing rust diseases (Afzal at al., 2015; 2022b). Breeding programs have successfully incorporated resistance genes from various sources to develop wheat varieties with durable resistance against different rust pathogens (Ellis et al., 2014; Ijaz et al., 2023). Continuous monitoring of rust populations and early detection of new virulent races are essential for effective disease management (Ali et al., 2020). Overall, addressing rust diseases in wheat is critical for ensuring global food security and maintaining stable wheat production in the face of evolving rust pathogen populations and changing environmental conditions (Lidwell-Durnin and Lapthorn, 2020).

Life cycle: a mycological perspective

Rusts, being obligate parasites, necessitate a living host to complete their life cycle, and although they do not usually cause the host's demise, they can substantially inhibit growth and productivity (Lorrain et al., 2019). Rust fungi exhibit a remarkable ability to generate up to five distinct spore types from corresponding fruiting body structures throughout their life cycle, a feature that may vary depending on the specific species (Kolmer et al., 2001). Conventionally, these morphological types have been denoted using Roman numerals for identification and classification purposes. This intricate life cycle and the diversity of spore types contribute to the adaptability and dispersal capabilities of rust fungi, making them a fascinating subject of study for researchers in the field of mycology (Mahadevakumar et al., 2021).

(0) Pycniospores are formed within specialized cup-like structures called pycnia or pycnidia. It is worth noting that the vast majority of fungi primarily reproduce asexually, relying on spore production as a means of propagation. Spores come in various colors, including colorless, green, yellow, orange, red, brown, or black, depending on the species and environmental factors. This wide range of colors reflects the diversity of fungal species and their unique adaptations for dispersal and survival in various habitats.

(I) Aeciospores are a type of spore produced by rust fungi as part of their complex life cycle. These spores typically contain two nuclei and are commonly observed arranged in chain-like formations within the aecium, a specialized structure where they are produced. The aeciospores play a crucial role in the dispersal and infection process of rust fungi, enabling them to colonize and infect new host plants. As part of the overall life cycle of rusts, aeciospores contribute to the successful reproduction and adaptation of these fungi in various environments.

(II) Urediniospores, have thin walls and play a crucial role in the spread and dissemination of rust diseases. Urediniospores are often responsible for secondary infections, leading to the rapid spread of rust diseases within a population of host plants. The urediniospores' adaptability and efficient dispersal mechanism are key factors in the epidemiology and survival of rust fungi. Urediniospores serve as repeating dikaryotic vegetative spores in the life cycle of rust fungi. The term “repeating stage” refers to their ability to cause auto-infection on the primary host, meaning they can re-infect the same host plant on which they were produced. This auto-infection capability enables rust diseases to persist and spread rapidly within a population of susceptible host plants.

(III) Teliospores are typically thick-walled and play a critical role in the survival of the rust fungus during adverse environmental conditions. When conditions become suitable again, the teliospores germinate, and basidiospores are produced.

(IV) When the teliospore germinates under favorable conditions, it gives rise to a specialized cell called a basidium. This happens during the Basidiospore stage. Within the basidium, two haploid nuclei (from the germinated teliospore) fuse together in a process called karyogamy, resulting in a diploid nucleus. The diploid nucleus then undergoes meiosis, a specialized type of cell division that produces four haploid nuclei. Each of the four haploid nuclei undergoes further division and becomes enclosed in small projections or sterigmata on the surface of the basidium. As the basidiospores mature, they are eventually released from the sterigmata on the basidium. These released basidiospores are now ready for dispersal. The basidiospores are dispersed by various means, such as wind or water. When they land on a suitable host, they germinate, giving rise to new hyphae, and the cycle of infection and disease development may begin again.

Management strategies of rust fungi

There have been several modern approaches to develop rust resistance in plants, particularly in agricultural crops. These approaches aim to improve crop productivity and reduce yield losses caused by rust diseases. Some of the common strategies include:

Conventional breeding

Traditional breeding methods involve crossing different plant varieties to introduce desired traits, including rust resistance. This approach has been successful in developing rust-resistant crop varieties. However, it can be time-consuming and may not always lead to high levels of resistance. Conventional breeding has been a cornerstone in developing rust-resistant crop varieties for many years (Acquaah, 2012; Brown and Caligari, 2008). While it has proven effective in delivering rust resistance, there are some limitations to this approach:

1. Conventional breeding involves multiple rounds of crossbreeding and selection to identify and combine desirable traits, including rust resistance, in the offspring. This process can take several years or even decades to develop a commercially viable and rust-resistant crop variety.
2. The success of conventional breeding relies on the availability of diverse genetic resources with the desired rust resistance genes. If the genetic pool of resistant varieties is limited, it may be challenging to find suitable sources of resistance.
3. Rust resistance is often a polygenic trait, meaning it is controlled by multiple genes. Identifying and tracking these genes through conventional breeding can be complex and time-consuming, as breeders need to manage and analyze multiple gene interactions.
4. Conventional breeding might not always lead to high-level resistance against rust pathogens. Some rust strains can overcome certain resistance genes over time, rendering the developed varieties susceptible to new virulent strains.

Gene mapping

Since the early 1950s, the development of genetics has been exponential with several milestones, including determination of DNA as the genetic material in 1944, discovery of the double-helix structure of DNA in 1953, the development of electrophoretic assays of isozymes (Markert and Moller, 1959) and a wide range of molecular markers that reveals differences at the DNA level (Semagn et al., 2006).

Gene mapping is a crucial process in genetics that involves identifying and locating genes on chromosomes (Paterson and Wing, 1993; Semagn et al., 2006). To initiate the mapping process, a suitable mapping population is selected, often derived from a cross between genetically distinct parents. The individuals in this population are then phenotyped for the trait of interest, such as rust resistance. Following phenotyping, DNA is extracted from each individual, and molecular markers, such as microsatellites or Single-nucleotide polymorphism (SNPs), are selected for genotyping. The genotypic data are analyzed for linkage, employing statistical methods, to identify markers associated with the target trait. A genetic map is constructed based on the identified linkages, providing insights into the relative positions of markers on chromosomes. QTL mapping may be performed to identify quantitative trait loci influencing the trait. Validation of markers and QTL in independent populations ensures the reliability of results. Fine mapping may be employed to narrow down genomic regions, and candidate genes within those regions can be explored. The ultimate goal is often the development of molecular markers for marker-assisted selection in breeding programs, enhancing the efficiency of crop improvement for traits like rust resistance (Semagn et al., 2006).

Smart breeding strategies

By combining the strengths of conventional breeding with these modern approaches, scientists can develop rust-resistant crops more efficiently and effectively. This integration of methodologies is known as "smart breeding" or "accelerated breeding", and it holds the potential to address rust diseases and other agricultural challenges more rapidly in the future.

Marker-assisted selection (MAS)

Marker-assisted selection (MAS) is a modern breeding technique that uses molecular markers linked to specific genes. This allows breeders to select for rust resistance more efficiently and accurately. By identifying markers associated with rust resistance, the breeding process can be expedited, leading to the development of improved rust-resistant cultivars. MAS is a powerful tool that has revolutionized the process of breeding rust-resistant crops (Kumar et al., 2023).

Regarding its working, scientists first identify specific DNA markers that are closely linked to genes responsible for rust resistance. These markers act as signposts or indicators for the presence of the resistance genes in a plant's genome. When scientists are exploring the genetic basis of rust resistance in plants, they search for specific DNA markers that are closely associated with the genes responsible for providing resistance. These markers serve as signposts or indicators that help researchers locate and track the presence of the resistance genes in a plant's genome (Rana et al., 2021).

In terms of how the process typically works, researchers start by collecting a diverse set of plant varieties or accessions, which includes both resistant and susceptible individuals to rust diseases. The DNA of these plant accessions is then analyzed to identify regions of the genome that show a consistent pattern of inheritance with rust resistance. These regions are called quantitative trait loci (QTLs) or genetic markers. By examining the genetic data, scientists can determine whether certain markers are more frequently present in the resistant plants. These markers are said to be "linked" to the genes that confer rust resistance. Once potential markers are identified, researchers test their association with rust resistance in larger populations of plants to ensure their reliability and accuracy. After validation, breeders can use these markers to select plants with the desired rust resistance genes in their breeding programs. They screen individual plants for the presence of specific markers linked to rust resistance, enabling them to identify promising candidates more efficiently. Breeders then cross the selected plants that carry the desired markers to develop new varieties that inherit the rust resistance genes. This process is known as marker-assisted breeding. Additionally, if multiple markers are associated with different rust resistance genes, breeders can combine these genes through gene stacking to create cultivars with enhanced and durable resistance. By utilizing these DNA markers, scientists can streamline the breeding process and focus on plants that have the potential to pass on the desired rust resistance traits to their offspring. This targeted approach significantly accelerates the development of rust-resistant crop varieties, contributing to sustainable and productive agriculture. When developing new plant varieties, breeders can analyze the DNA of individual plants to identify those that carry the desired markers associated with rust resistance. This step is much faster and more accurate than traditional phenotypic screening methods, which rely on observing the plant's physical characteristics. By using MAS, breeders can select plants with rust resistance genes early in the breeding process, even before the plants grow to maturity (Pandurangan et al., 2021; Mallick et al., 2022). This early selection allows breeders to focus on the most promising candidates, reducing the time required to develop rust-resistant cultivars. MAS enables precise selection for specific resistance genes, allowing breeders to combine multiple resistance genes to create cultivars with broad-spectrum resistance. This approach minimizes the risk of rust pathogens evolving to overcome single resistance genes. Breeders can efficiently stack multiple resistance genes using MAS, which is crucial for developing durable resistance against evolving rust pathogen populations (Shahin et al., 2023). By selecting plants based on their molecular markers, MAS increases the chances of obtaining rust-resistant offspring in each breeding cycle (Babu et al., 2020). This efficiency results in more successful and rapid development of rust-resistant cultivars. Overall, MAS significantly expedites the breeding process, accelerates the development of rust-resistant crop varieties, and contributes to improved agricultural productivity by reducing yield losses due to rust diseases. It complements conventional breeding techniques and has been widely adopted in modern plant breeding programs to address rust and other plant diseases effectively (Gupta et al., 2010).

Challenges in marker-assisted selection for wheat improvement

MAS holds promise for improving wheat crops, yet its application is constrained by several limitations. Wheat exhibits complex traits influenced by multiple genes, complicating the identification and selection of relevant markers. Limited marker coverage poses a challenge, as not all traits have associated markers, hindering comprehensive MAS implementation (Holland, 2004). Factors such as linkage disequilibrium and recombination can diminish the precision of marker-gene associations over time (Jiang, 2013). Environmental influences further impact MAS efficacy, as markers identified in one setting may not reliably predict trait expression in different conditions. The costs and infrastructure requirements for marker analysis, including specialized equipment and skilled personnel, may limit adoption in resource-constrained breeding programs. Genetic diversity across wheat varieties may render markers less universally applicable. The long breeding cycles of wheat and the necessity for field testing still persist, undermining the purported acceleration of breeding processes. Ethical and regulatory considerations, especially regarding genetic modification, add additional complexity to MAS adoption. Despite these challenges, ongoing advancements in genomics and breeding methodologies aim to enhance MAS effectiveness and integrate it more seamlessly into wheat improvement strategies.

Genetic engineering

Genetic engineering or genetically modified organisms (GMOs) have been explored to introduce rust resistance genes into susceptible crops (Camacho et al., 2014; Dawkar et al., 2018). By inserting specific rust resistance genes from other plant species into susceptible crops, scientists can develop plants with enhanced resistance. Genetic engineering, including the creation of genetically modified organisms, has been explored as a strategy to introduce rust resistance genes into susceptible crops. This approach involves inserting specific genes from other plant species that confer rust resistance into the genome of the target crop to develop plants with enhanced resistance (Ali et al., 2018; Esse et al., 2019).

To make plants resistant to rust using genetic engineering, scientists find and separate the genes that protect some plants from rust. These genes might code for proteins that directly combat the rust pathogen or regulate the plant’s defense responses. Once the rust resistance genes are identified, they are inserted into the genome of the target crop plant. This is achieved through genetic engineering techniques such as Agrobacterium-mediated transformation or gene gun bombardment. The introduced rust resistance genes are now part of the crop plant’s genetic makeup. When the plant is exposed to rust pathogens, these genes produce proteins or molecules that help the plant resist or defend against infection (Shrawat and Armstrong, 2018).

Genetic engineering can offer several advantages when introducing rust resistance into crops:

1. Specific resistance genes can be precisely selected and transferred, allowing for targeted resistance against specific rust pathogen strains.
2. Compared to conventional breeding, genetic engineering can expedite the process of introducing rust resistance genes, potentially leading to faster development of resistant crop varieties.
3. Multiple resistance genes can be introduced into a single crop plant through genetic engineering, enhancing the durability of rust resistance.

4. Genetic engineering allows the transfer of rust resistance genes from diverse sources, including unrelated plant species, broadening the genetic pool for resistance.

Concerns and challenges

The use of GMOs, however, remains a subject of debate and regulation in many regions. Some concerns related to GMOs and genetic engineering in agriculture includes:

1. Potential ecological consequences and unintended effects on non-target organisms.
2. Concerns about the safety of consuming GMOs, although extensive studies have not shown any major health risks so far.
3. Worries that the widespread adoption of GMOs may lead to a loss of biodiversity if they become dominant in agriculture.
4. Issues surrounding the control and ownership of genetically modified seeds by biotechnology companies.

As a result of these concerns, many countries have implemented strict regulations for the testing, cultivation, and trade of GMOs, and public opinion varies widely on the acceptance of genetically modified crops.

Overall, genetic engineering can offer promising solutions for rust resistance in crops, but the ethical, environmental, and regulatory considerations make it a complex and polarizing subject in modern agriculture. Different regions and countries have taken different approaches to the regulation and adoption of GMOs based on their specific cultural, economic, and environmental contexts (Graef et al., 2012).

Gene editing

Gene editing techniques like CRISPR-Cas9 offer precise and targeted modifications to a plant's genome (Afzal et al., 2023). It allows scientists to add, delete, or modify specific genes associated with rust resistance (Hafeez et al., 2021). Gene editing provides a more controlled and predictable way of developing rust-resistant crops compared to traditional genetic engineering (Altaf et al., 2022). Gene editing techniques, with CRISPR-Cas9 being one of the most prominent, have revolutionized the field of genetic manipulation in plants and offer significant advantages over traditional genetic engineering methods. When it comes to developing rust-resistant crops, gene editing provides a more precise, controlled, and predictable approach (Chen et al., 2019; Pickar-Oliver and Gersbach, 2019). Here is how gene editing contributes to rust resistance in plants:

1. Gene editing, particularly using CRISPR-Cas9, allows scientists to target specific DNA sequences in a plant's genome with high precision. This means they can directly modify or edit the genes associated with rust resistance without introducing additional genetic material from other species.
2. With gene editing, it is possible to introduce targeted mutations in the plant's genes. This can include introducing natural variations found in rust-resistant plant species or disabling specific genes that the rust pathogens exploit for infection.
3. Unlike traditional genetic engineering, which involves the insertion of foreign genes into the plant's genome, gene editing allows for the modification of existing genes without introducing additional genetic material. This can mitigate some concerns related to GMOs.
4. Gene editing techniques are generally faster and more efficient compared to traditional breeding or genetic engineering methods. The ability to directly modify specific genes means researchers can develop rust-resistant crop varieties in a shorter timeframe.
5. Gene editing allows scientists to simultaneously modify multiple genes associated with rust resistance, a process known as gene stacking. This can create crop varieties with enhanced resistance to multiple rust pathogen strains.
6. While gene editing is precise, there is always the risk of off-target effects where unintended mutations occur. Nevertheless, advances in gene editing technologies, such as CRISPR-Cas9, have greatly improved the specificity and accuracy of the process.
7. Some countries and regions have adopted more relaxed regulations for gene-edited crops compared to traditional GMOs, potentially facilitating the deployment of rust-resistant varieties developed through gene editing.

Gene editing in agriculture: navigating safety, ethics, and regulation for rust-resistant crops

It is essential to note that while gene editing offers great promise, the technology is still relatively new, and researchers must rigorously assess the safety and unintended effects of edited crops before widespread adoption. Additionally, public acceptance, ethical considerations, and regulatory policies play significant roles in determining the broader use of gene-edited crops, including those with rust resistance traits. Nevertheless, gene editing presents an exciting avenue for developing rust-resistant crops and addressing other agricultural challenges more effectively.

Challenges and boundaries in gene editing

There are notable challenges and boundaries in the application of gene editing for rust resistance in wheat (Chan and Arellano, 2016; Uddin et al., 2020).

1. One primary concern is the potential unintended consequences of genetic modifications, such as off-target effects or unintentional changes to other important traits. Ensuring the specificity and safety of gene edits is critical to avoid any negative impacts on wheat quality or unintended environmental consequences.
2. Moreover, regulatory frameworks surrounding genetically modified organisms vary globally, and navigating these diverse regulations poses a significant obstacle for the widespread adoption of gene-edited wheat varieties.
3. Ethical considerations, public perception, and acceptance of genetically modified crops also play a crucial role in determining the success and societal implementation of gene editing technologies in agriculture.

Striking a balance between harnessing the potential benefits of gene editing for rust resistance and addressing these challenges will be essential for the responsible and sustainable advancement of this technology in wheat breeding.

RNA interference (RNAi)

RNAi is a natural biological process that can be harnessed to silence specific genes in pests and pathogens, including rust-causing fungi (Panwar et al., 2018). By using RNAi, researchers can inhibit the expression of rust pathogen genes and reduce disease severity in plants (Puyam et al., 2017). RNAi is a powerful and natural biological process that has been harnessed for its potential in developing rust- resistant crops (Halder et al., 2022). Here is how RNAi works and how it can be used to combat rust-causing fungi:

1. RNAi is a regulatory mechanism found in many organisms, including plants and fungi. It involves the silencing or down-regulation of specific genes through the action of small RNA molecules, particularly small interfering RNAs (siRNAs) or microRNAs (miRNAs) (Aydinoglu, 2022).
2. In the context of rust resistance, researchers can identify critical genes in the rust-causing fungi that are essential for the infection process or the establishment of disease. They then design and introduce corresponding siRNAs or miRNAs into the plant (Ossowski et al., 2008).
3. Once inside the plant cells, these siRNAs or miRNAs can target the complementary sequences of the pathogen's genes and bind to them. This binding triggers the degradation or suppression of the pathogen's RNA, preventing the expression of vital proteins required for the rust infection process (Pumplin and Voinnet, 2013).
4. By inhibiting the expression of rust pathogen genes, the RNAi technology can effectively impede the growth and spread of the pathogen in the plant. This reduction in the pathogen's activity can lead to a decrease in disease severity or even confer complete resistance to rust (Yin et al., 2011).

RNAi offers several advantages for developing rust-resistant crops. RNAi can be designed to target specific genes in the rust-causing fungi, making it a highly targeted approach. Since RNAi targets conserved genes in the pathogen, it can provide resistance against multiple strains and races of the rust pathogen. RNAi-based approaches are generally considered safe for the environment because they rely on endogenous biological processes that occur naturally in plants and other organisms (Svoboda, 2020). However, there are some challenges associated with the practical application of RNAi for rust resistance:

Delivery

Efficient delivery of RNAi molecules into plant cells and achieving sustained gene silencing remains a technical challenge.

Specificity

Ensuring that the RNAi molecules only target the pathogen genes and not the plant's own genes is crucial to avoid unintended effects.

Long-term stability

Maintaining stable and heritable RNAi-mediated resistance over generations is a significant concern in crop breeding.

Despite these challenges, RNAi shows considerable potential as a valuable tool in the development of rust-resistant crops, and ongoing research in this area holds promise for future agricultural applications

Induced systemic resistance (ISR)

ISR is a strategy that involves treating plants with certain compounds or beneficial microorganisms to activate their natural defense mechanisms. These defense responses can make the plant more resistant to rust and other pathogens. ISR is a fascinating strategy used in agriculture to enhance a plant's natural defense mechanisms against pathogens, including rust-causing fungi (Thabet et al., 2008). Here's how ISR works and its implications for developing rust-resistant crops:

1. ISR involves treating plants with certain beneficial microorganisms or compounds. These can include certain strains of bacteria, fungi, or even chemical elicitors that can induce the plant's defense responses (Sowndhararajan et al., 2013; Mishra et al., 2015; Salwan et al., 2022).
2. When the plant is exposed to these beneficial microorganisms or compounds, it triggers a series of biochemical and molecular responses within the plant. These responses activate the plant's innate defense mechanisms (Van Wees et al., 2008).
3. The induced defense responses not only occur locally at the site of application but also spread throughout the entire plant, leading to what is known as a systemic acquired resistance (SAR) or ISR (Kamle et al., 2020).
4. The activated defense responses make the plant more resistant to various pathogens, including rust-causing fungi. The enhanced resistance can result in reduced disease severity and lower susceptibility to rust infections (Ellis et al., 2014).
5. ISR often involves priming the plant's immune system. The primed plant is better equipped to recognize and respond more rapidly and effectively to subsequent attacks by rust pathogens (Ton et al., 2009).
6. One of the benefits of ISR is its non-specific nature. While it is induced by specific microorganisms or compounds, the resistance conferred is often effective against a broad range of pathogens, making it a valuable tool in disease management (Kuc, 2001).
7. ISR is considered an environmentally friendly approach because it relies on stimulating the plant's own defense mechanisms rather than using chemical pesticides (Zehra et al., 2021).

Challenges in harnessing ISR for wheat rust resistance

ISR presents a promising approach for enhancing rust resistance in wheat, but it also comes with its set of challenges and boundaries. ISR involves the activation of the plant's innate defense mechanisms through the application of beneficial microorganisms or elicitors, providing a sustainable and environmentally friendly method for disease management (Bellameche, 2020).

1. One challenge is the complexity of the plant-microbe interactions, as the effectiveness of ISR can vary depending on the specific wheat variety, the rust pathogen involved, and environmental conditions. Achieving consistent and reliable results across diverse agricultural settings poses a significant hurdle for widespread adoption.
2. Furthermore, the translatability of ISR from controlled laboratory conditions to field environments presents another boundary. Implementing ISR on a large scale requires a deep understanding of the ecological factors influencing the interactions between plants, microbes, and pathogens in real-world agricultural ecosystems. The durability of induced resistance over time and its potential interference with other agricultural practices need thorough investigation.
3. Economic considerations and the scalability of ISR also pose challenges. Developing and applying microbial products or elicitors on a commercial scale may be costly, and farmers need cost-effective solutions to justify their adoption. Moreover, educating farmers about the benefits and practices associated with ISR is crucial for its successful integration into agricultural systems.

Overcoming challenges and embracing ISR for enhanced wheat rust resistance

While ISR holds great potential for enhancing rust resistance in wheat, addressing challenges related to variability, translatability, economic feasibility, and farmer awareness is essential for its successful implementation and widespread adoption in real-world agricultural settings. Researchers and farmers are exploring the application of ISR to improve rust resistance in crops. By utilizing beneficial microorganisms or compounds that induce systemic resistance, it is possible to enhance the plant's overall resistance to rust and other diseases. ISR complements other strategies for rust management, such as breeding for resistance or using chemical fungicides, and can contribute to sustainable and integrated disease management practices in agriculture. Like other strategies, successful application of ISR depends on factors such as the specific crop, the type of rust pathogen involved, and the environmental conditions. As research in plant-microbe interactions continues to advance, the use of ISR is expected to gain further prominence in agriculture for combating rust and other plant diseases.

Bio fungicides

Bio fungicides are environmentally friendly alternatives to chemical fungicides. They contain living organisms such as bacteria or fungi that are antagonistic to rust pathogens. When applied to crops, bio fungicides can suppress rust infections (Moricca and Ragazzi, 2008). Bio fungicides are an eco-friendly and sustainable approach to managing plant diseases, including rust, in agriculture. These products consist of living microorganisms, such as bacteria or fungi that have antagonistic properties against rust pathogens (Rosas-Jáuregui et al., 2022). When applied to crops, bio fungicides can suppress rust infections through various mechanisms:

1. The living microorganisms in bio fungicides produce compounds or enzymes that directly inhibit the growth and development of rust-causing fungi. They can compete with the pathogens for resources, limiting their ability to infect and colonize plant tissues (Nega, 2014).
2. Bio fungicides can trigger the plant's defense mechanisms, such as systemic acquired resistance or induced systemic resistance (Shoresh et al., 2010) similar to the ISR strategy discussed earlier. This primes the plant to be more resistant to subsequent rust infections.
2. Some bio fungicides establish a beneficial presence on the plant surface, forming a protective barrier. This colonization prevents rust spores from finding suitable sites for infection (Santra and Banerjee, 2020).
3. Bio fungicides are generally considered safe for the environment, non-toxic to non-target organisms, and pose minimal risk of developing resistance in pathogens (Ezeorba et al., 2023).
4. Using bio fungicides in rotation or in combination with other disease management practices, such as chemical fungicides or resistant crop varieties, can help reduce the risk of resistance development in plant pathogens (Valarmathi, 2018).

Constraints in the bio pesticide landscape for sustainable plant disease management

There exist challenges and constraints in the widespread adoption of bio pesticides. These constraints may include factors such as limited efficacy under certain environmental conditions, variable performance across different crop-pest systems, and economic considerations. As the field of bio pesticides continues to evolve, addressing these constraints will be crucial for maximizing their potential contribution to effective and sustainable plant disease management. The review emphasizes the need for ongoing research, innovation, and strategic implementation to overcome these limitations and fully harness the benefits of bio pesticides in shaping the future of plant protection (Meshram et al., 2022).

Maximizing the efficacy of bio fungicides in rust management

It is important to note that the efficacy of bio fungicides can vary depending on factors like the specific crop, the rust pathogen species, and environmental conditions. Therefore, proper application timing and integrated disease management strategies are crucial for maximizing their effectiveness. Bio fungicides offer a valuable option for sustainable and environmentally friendly disease management in agriculture. As the demand for safer and more sustainable agricultural practices increases, bio fungicides continue to gain popularity as an essential tool for managing rust and other plant diseases while minimizing the impact on ecosystems and human health.

Significance of developing climate-resilient varieties to achieve target of food security

Climate change can impact the prevalence and severity of rust diseases (Sukumaran et al., 2021). Developing climate-resilient crop varieties that can withstand changing environmental conditions, such as temperature and humidity, can indirectly contribute to rust resistance (Wani et al., 2022). Climate change can have significant implications for the prevalence and severity of plant diseases, including rust diseases. Developing climate-resilient crop varieties is a proactive approach to address the challenges posed by changing environmental conditions and indirectly enhance rust resistance (Chakraborty and Newton, 2011). Here is how climate-resilient varieties contribute to rust management:

1. Climate-resilient crop varieties are specifically bred or selected to withstand the changing climatic conditions, such as temperature extremes, altered precipitation patterns, and shifts in humidity. These varieties have better chances of maintaining their health and productivity even under adverse climatic conditions, which can influence rust development (Mir et al., 2022).
2. Climate-resilient varieties are designed to be more tolerant to environmental stresses, including drought, heat, and excess moisture. When plants are under less stress, their natural defense systems are better equipped to combat rust infections (Mafakheri and Kordrostami, 2020).

3. Climate-resilient varieties may exhibit more robust immune responses due to their improved physiological and metabolic adaptations. These enhanced immune responses can indirectly contribute to rust resistance (Kim et al., 2021).
4. With climate change, some regions may experience longer growing seasons. This can potentially create more favorable conditions for rust pathogens to reproduce and spread. Climate-resilient varieties that have extended or flexible growing seasons can help avoid peak rust infection periods (Duveiller et al., 2007).
5. Climate-resilient varieties often involve the incorporation of diverse genetic traits to ensure adaptability to various environmental conditions. This genetic diversity can indirectly contribute to improved rust resistance by broadening the range of defense mechanisms (Prasanna et al., 2013).
6. Climate change may also lead to the emergence of new rust pathogen strains. Climate-resilient varieties that possess diverse resistance genes can better withstand the onslaught of these evolving pathogen populations (Chakraborty et al., 2011).
7. Combining climate-resilient varieties with other disease management practices, such as bio fungicides, resistant crop rotations, and cultural practices, can form an effective integrated approach to control rust and other diseases (Pannu et al., 2010).

Developing climate-resilient crop varieties is a long-term strategy that requires extensive breeding efforts and a thorough understanding of the interactions between climate, rust pathogens, and plant physiology. As climate change continues to pose challenges to agriculture, the development and deployment of climate-resilient varieties become increasingly crucial for sustaining food production and mitigating the impacts of rust diseases and other stressors on crops.

CONCLUSIONS

In conclusion, wheat is an essential crop for global food security, but it faces significant challenges due to rust diseases that cause substantial yield losses. To address these challenges, modern approaches such as Marker-Assisted Selection (MAS), genetic engineering, gene editing with CRISPR-Cas9, RNA interference (RNAi), and Induced Systemic Resistance (ISR) have been explored to develop rust-resistant wheat varieties efficiently and sustainably. MAS allows for the precise selection of rust-resistant plants, reducing the time needed to develop improved cultivars. Genetic engineering techniques offer the potential to transfer rust resistance genes from other species, but GMOs remain controversial and subject to regulation. CRISPR-Cas9 provides a precise and controlled method for modifying wheat's genome and enhancing its innate resistance to rust. RNAi exploits a natural defense mechanism in plants to inhibit the expression of rust pathogen genes, reducing disease severity. ISR involves treating plants with beneficial microorganisms or compounds to activate their defense responses and make them more resistant to subsequent rust infections. Bio fungicides with living microorganisms antagonistic to rust pathogens offer an eco-friendly alternative to chemical fungicides. Climate-resilient wheat varieties are being developed to withstand changing environmental conditions induced by climate change, indirectly enhancing rust resistance and ensuring stable production. Integrating modern approaches with traditional breeding and sustainable agricultural practices is vital to enhance food security and combat rust diseases effectively.

Continued research and development are necessary to ensure the sustainability of wheat production and global food security amidst climate change and evolving pathogen populations. By implementing these strategies and continuously improving our understanding of rust resistance mechanisms, we can work towards securing the world's wheat supply and feeding the growing global population. Collaboration between scientists, breeders, farmers, policymakers, and the public is crucial in this endeavor to address the complex challenges posed by rust diseases and secure the future of wheat production.

AUTHORS' CONRIBUTIONS

AA conceived the idea for the review article and led the project; SM and AA accumulated relevant literature for the article; HHN wrote and composed the review article; MA collaborated with HHN to contribute to the authorship of the manuscript; SS ensured the precision of the reference list through meticulous examination and verification; AGK provided recommendations for discussion section titles; AA conducted a thorough review of the manuscript and provided valuable insights for further enhancement.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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