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Review Article

Thwarting the Blight: A Comprehensive Review of Traditional and Molecular Germplasm Screening Techniques for Black Spot Resistance in Roses

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ABSTRACT

Diplocarpon rosae causing rose black spot disease, is one of the most devastating pathogens, that affect the quality of roses, and is responsible for huge yield losses, worldwide. Many approaches have been applied to control this disease including developing resistance variety. However, this review widely evaluates different screening germplasm methods to control the black-spot disease in rose. Additionally, in this review, many major issues influencing the black-spot disease resistance, including environmental factors, plant-pathogen interaction and genetic diversity, providing a complete thoughtful of the multifaceted nature of this disease. Moreover, the variety of screening technique ranging from conventional field assessment to contemporary molecular approaches, emphasizing their respective benefits and restrictions. But, the finding and employing new resistance genes is very difficult due to highly genetic diversity of this pathogen, especially, when their interaction of this pathogen to plant are not completely understood. Because, various isolates and strains of pathogen can relate in diverse ways with different germplasm, making it challenging to identify uniform resistance among all strains. Furthermore, many environmental factors including light, temperature and humidity support to increase the disease development, leading reduce the resistance and tolerance of plant against pathogen. Whereas, developing resistance germplasm might be helpful to control this disease and reduce pathogen infection in plants. In this regard, many plant-omics studies such as transcriptome, genome re-sequencing and proteomics have been widely studied to find out candidate resistance (R) protein and genes, which related to the black-spot disease. This review seeks to provide researchers as well as growers and breeders with a through recourse that combine recent information on the assessment of rose germplasm against black spot disease resistance. By employing newly approaches, we aimed to accelerate the growth of rose varieties, that are beautifully attractive and strong in the appearance on this determined blight. In the last, our collective finding to addresses the issues could be increase the sustainability and visual attractiveness of rose cultivation for future generations.

Keywords: Rose, germplasm, screening, black spot, techniques.

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INTRODUCTION

Rose belongs to the largest family (Rosaceae), which have a long cultivation history, and developing as a prominent ornamental floricultural plant in the floriculture field (Schulz et al., 2009). The genus comprises more than 150 species in worldwide (Debray et al., 2019). Among them, *Rosa chinensis*, also known as Chinese flower, is most prominent and cherished flower in China and play an important role in cultural exchange across regions (Yang et al., 2023).

The Rose is esteemed as the designated city flower in numerous Chinese urban centers, contributing significantly to urban landscapes. Notably, the petals of roses also serve as a natural source of fragrances and flavorings for diverse industries such as perfumery, culinary arts, and pharmaceuticals (Guterman et al., 2002). As compared to other cut flowers, the rose ranked as the first flowering plant on the basis of acreage, production, and consumption. But, now a days the production of this crop is continuously decreasing due to some biotic and abiotic factors including plant diseases. More than ten fungal and bacterial diseases reduce the production of this crop, which causes approximately 30 fungal and bacterial pathogens worldwide (Debener and Byrne, 2014; Nazarov et al., 2020). The disease and causal organism details are presented in Table 1. This disease can lead to significant damage, and in some cases, result in the death of plants (Wang et al., 2023). From which, black spot disease is one of the most important damaging and destructive diseases of rose. In 1815, the disease was first time discovered in Sweden, caused by *Marssonina rosae* (Li et al., 2023). Later, it was spread to all the growing countries worldwide, and posed significant threats, particularly in densely populated open field cultivations (Debener, 2019). *Diplocarpon rosae* wolf (syn: *Marssonina rose*) is very serious and devastating pathogen, causing black spot disease in rose, and responsible for major economic losses globally (Chandel et al., 2017). Under favorable environmental condition, initially the conidia produce infection in the plant material and survived long time on the leaves, stems, dropped, thorns and buds (Rehman et al., 2012). The Conidia of this pathogen are spread through various factors such as; wind, rain and animal vectors, like plant insects (Saideekshith et al., 2020). After spreading conidia, the upper leaf surface parts of plants showed dark circular patches symptoms with slight feathered edges. Interestingly, the lower epidermis ruins unaffected. The resultant symptoms encompass chlorosis encircling the lesion, culminating in leaf defoliation (Blechert and Debener, 2005; Gachomo et al., 2006). Previous studies pinpointed *Alternaria* sp. as the primary causal agent behind rose black spot disease. For instance, investigations by (Natali et al., 2022) involved collecting symptomatic leaf samples from Xi'an, Xianyang, Baoji, and Weinan, with molecular and morphological analyses eventually identifying the pathogenic agent responsible for the disease as *Alternaria alternata* (Si-jin et al., 2019). In another similar studied cases (V. M. Whitaker et al., 2010) found more than ten races of *D. rosae* in Europe and North America. While roses have been cherished for generations due to their visual and olfactory splendor, the persistent threat of black spot disease has posed a considerable challenge for aficionados and cultivators (Irwin, 1994). Many fungicides are available in the market to control this disease, but new races of this pathogen show resistant against these agrochemicals (Dong et al., 2023). Resistant germplasm is highly and useful approach to control and manage blackspot disease in rose (Schulz et al., 2009; Tran et al., 2014). In this review we present "Thwarting the Blight: A Comprehensive Review of Traditional and Molecular Germplasm Screening Techniques for Black Spot Resistance in Roses. This comprehensive review explains the diverse germplasm screening techniques and methodologies scientists employ to develop black spot-resistant roses.

Table 1. Lists numerous diseases of roses and their causal organism

Disease	**Causal agent**	**Reference**
Black spot	*Alternaria alternata, Diplocarpon rosae* and *Gnomoniopsis rosae*	(Debener, 2019; Li et al., 2023)
Fusarium wilt	*Fusarium rosicola*	(He et al., 2021)
Anthracnose	*Colletotrichum siamense*and *C. truncatum*	(Feng et al., 2019; Mahadevakumar et al., 2019)
Powdery mildew	*Podosphaera pannosa*	(Leus, 2005)
Gray mold	*Botrytis cinerea*	(Liu et al., 2019)
Leaf blotch	*Guignardia aesculi*and *Pestalotiopsis clavispora*	(Banks and Percival, 2012; Feng et al., 2014)
Branch blight	*Phytopathora megasperma*	(Nagai et al., 1978)
Downy mildew	*Peronospora sparsa*	(Salgado-Salazar et al., 2018)
Rust	*Phragmidium mucronatum, P. disciflorum, P. chayuensis, P. cibanum*and *P. zangdongii*	(Liu et al., 2018; NICOLAE and Luminița, 2022)
Leaf spot	*Cercospora rosicola*	(Yasin et al., 2016)

Shoot dieback	*Verticillium albo-atrum* and *Lasiodiplodia pseudotheobromae*	(Kamińska et al., 2003; Wee et al., 2017)
Stem and root rot	*Rhizoctonia solani* and *Fusarium oxysporum*	(Barguil et al., 2009; Priyatmojo et al., 2001)
Dry brown spot	*Fusarium clavum*	(Manganiello et al., 2021)
Crown gall	*Agrobacterium tumefaciens, A. vitis, A. radiobacter, A. deltaense, A. nepotum, A. larrymoorei* and *A. viscosum*	(Kawaguchi et al., 2008; Mafakheri et al., 2019; Rhouma et al., 2008)

OVERVIEW OF BLACK SPOT DISEASE IN ROSES

Black spot disease is one of the most important and aggressive diseases, caused by the hemibiotrophic fungus *D. rosae* (Gachomo et al., 2006).The pathogen predominant asexual reproduction is distributed by splash water and direct contact in roses, which leading defoliation of the plant, reduced flower production, and sometimes mortality of leaves and plants in the field (Gachomo, 2005). The major symptom of black spot disease in plants such as the appearance of circular, black, or dark brown spots on the leaves of the rose plant (Singh et al., 2012). After that, the leaves show a yellowish color with a halo around them and reduce prematurely of plants, respectively (Figure 1) (Chouhan et al., 2018). In rainy or humid weather, the fungus proliferates on the leaves and causes infection (Thind et al., 2004). Poor air circulation around the plants also contributes to their development.

Figure 1. Symptoms of black spot disease of rose caused by *D. rosae*. Some infected leaves show yellow with leaf spots, and some show prematurely of the leaves.

The life cycle of black spot disease of rose

Black spot disease is attributed to representing its perfect stage and imperfect stage of this pathogen is known as *Marssonina rosae* (Lib.) Lind. This fungus is widely distributed globally and poses a significant challenge in cultivating outdoor roses (Gachomo et al., 2006). Under favorable temperature, the fungus grows rapidly on the leaves and causes infection (Thind et al., 2004). Poor air circulation around the plants also contributes to their development. When left to overwinter at Wisley, it was observed that only the *D. rosae* strain from Silwood Park, and not the local strain, produced apothecia on fallen rose leaves (Cook, 1981). Spore-bearing structures develop within two weeks after infection, releasing spores that act as a secondary or recurring source of inoculation. During the winter and early spring, conidia were dispersed and carried by rain to a height of 5–10 cm above the infected fallen leaves (González-Domínguez et al., 2014). After 3-16 days of infection, the disease symptoms are observed in the leaves, show disorders, and fall down on the soil, respectively **(Figure 2)** (Cook, 1981; Gachomo and Kotchoni, 2007; Gachomo, 2005).

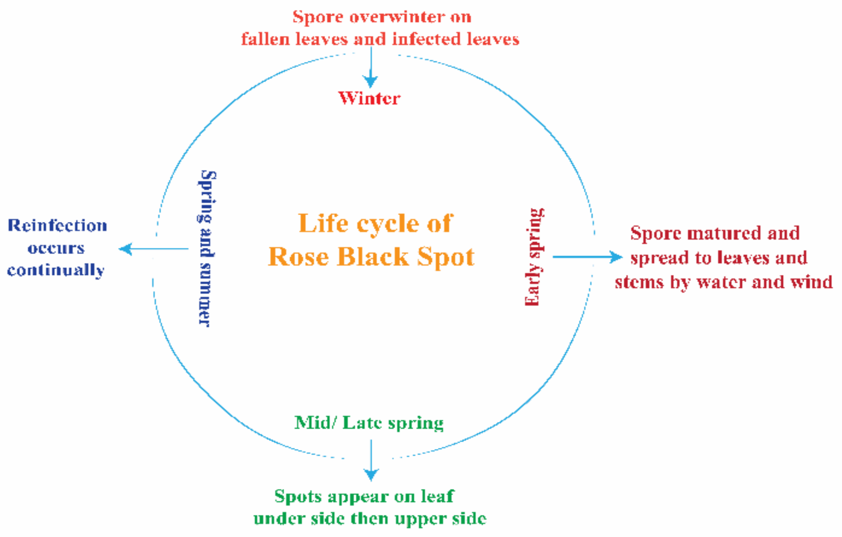

Figure 2. The life cycle of back spot pathogen. The spore of the pathogen produced heavy infection in the plant in both spring seasons late and early, as well as in the winter.

MANAGEMENT AND CONTROL

Previously, many techniques were applied to control this disease, including fungicides, biocontrol agents, and growing resistant germplasm, which carrying resistance genes against pathogen infection (Gachomo et al., 2009; Prasad et al., 2002; Schulz et al., 2009). Among them, growing resistant germplasm against this disease, is the most powerful approach to control the pathogen infection of early and late stage. Identifying and utilizing resistant germplasm in the context of black spot disease, especially in roses, is essential for several reasons (Lopez Arias et al., 2020). Resistant germplasm is most important factor of combined disease management approaches (Drenth et al., 2004), which was depend on the ability of different species (Erwin and Ribeiro, 1996). It is alternative approach to chemical fungicides and also decrease the hazards of agro-chemicals fungicides or pesticides and other disease control measures. Resistance germplasm are also suitable for environment and sustainable gardening practices and also reduce the chemical expenses, labor for disease management and enhance economic benefits (Heydari and Pessarakli, 2010). Resistance cultivars increase the sustainability of rose gardens through decreasing the affecting issue including disease and reduce the necessity for continuing intervention (Collins and Qualset, 1998). This variety increase the beauty of landscapes and decrease the likelihood of extensive outbreak, that can influence on rose monoculture plantings (Leung et al., 2003). By studying and employing of resistant cultivar delivers valuable insights into the genetics, interaction of host plant-pathogen, and as well as development of resistance mechanisms.

Preservation of Biodiversity

By recognizing and protecting naturally resistant rose germplasm, we play a crucial role in maintaining genetic diversity among rose species, which is vital for future breeding program and conservation of biodiversity. In addition, identification of resistance cultivar against black spot disease are critical for effective disease management, economic viability, environmental sustainability, and the long-term vitality and resilience of rose plants. This approach exemplifies a positive and sustainable technique for plant health in the garden and horticultural field (Roberts and Mattoo, 2018).

Pathogen Diversity

D. rosae is the major fungal pathogen causing black spot disease in roses (Neu and Debener, 2019). Although, there are variations within the species, it is commonly known as single species (MacArthur, 1965), which are crucial to known that various rose cultivars showed different susceptibility and resistance to black spot disease (Whitaker, 2009). This variation stems from the genetic variances among the various rose cultivar based on the following parameters.

Selection Pressure

The fungicides application and the growing of vulnerable varieties exert selection pressure on the pathogen. Regular application of fungicides can increase resistance within the pathogens, which is hazard for crop (Van Den Bosch et al., 2011). The interaction between a pathogen and its host plays a essential role in the virulence growth. Its populations can evolve in response to particular host defense or alterations in the host genetic characteristics (Stevens et al., 2021). Genetic diversity in the pathogens might be result to developed new strains with diverse level of virulence, with more virulent strains potentially having a competitive advantage in infecting vulnerable hosts (van Baalen and Sabelis, 1995).

Environmental Factors

Environmental factors including, humidity and temperature, reduce the growth of plants and favor to spread the disease in field. Due to this the infected ability of pathogen is increase and cause disease and cause disease (Gullino et al., 2018). To combat black spot disease and pathogen infection, selecting and breeding rose resistance cultivars play an essential role, which decrease the infection risk in plants (Debener and Byrne, 2014).

The Role of Germplasm in Disease Resistance

Germplasm play an important role in disease, showed different type of susceptibility and resistance against pathogens (Shii et al., 1994). It includes different various types of genetic material, such as seeds, pollen, and tissues, that are used for research and breeding purposes. The ability of plants is resist to pathogen infection and diseases is regulate by particular genes or genes combinations, that protect them to specific disease or pathogens (Reinert and Bajaj, 2013). Germplasm collections involve a variety of genotypes, each possessing distinct genetic characteristics. This genetic diversity serves as a vital resource for discovering and utilizing resistance genes against different diseases (Kumar et al., 2022). Plant breeders employ germplasm collections to pinpoint and incorporate beneficial traits, such as resistance against various diseases, from wild or landrace populations into cultivated varieties. This process known as introgression, results developed the new variety with increase resistance (Zamir, 2001). Through cross-breeding resistant cultivar, breeders increase the overall resistance of cultivated varieties (Karim et al., 2021). Germplasm serves as a valuable resource for detection of particular genes or quantitative trait loci (QTLs), which related to disease resistance. Molecular markers associated with these genes facilitate marker-assisted selection (MAS), leading to more efficient breeding results (Ashraf and Foolad, 2013). Additionally, germplasm facilitate researchers to explore the genetic and molecular mechanisms, that contribute to disease resistance. Investigating resistant genotypes provides scientists with understandings into the defense pathways of plants (Ali and Yan, 2012). However, due to new strains and nature of pathogens previously resistant varieties exhibited highly susceptible to disease (O'Brien, 2002). Germplasm collections functions as a respiratory of different genotypes, offering a wide range of potential resistance sources to combat developing threats (McCouch et al., 2012). Germplasm and gene banks are established to conserve genetic resources, including disease-resistant genotypes. These institutions safeguard plant diversity for future generations and unforeseen challenges (Smale and Jamora, 2020). Germplasm collections may include genotypes adapted to specific regions or environmental conditions, some exhibiting natural resistance to locally prevalent diseases (Hawtin et al., 1997). In perennial crops like fruit trees and grapevines, rootstocks from disease-resistant germplasm confer resistance to the scion, the upper part of the plant (Reisch et al., 2012). Germplasm in roses, as in other plants, refers to the genetic material that carries the hereditary information of the species (Bado et al., 2015). Genetic diversity, both within and among species, is the raw material for the future improvement of all crops(Falcon and Fowler, 2002). This genetic material is stored as seeds, cuttings, or other plant propagation materials. Germplasm is the foundation for breeding programs and the development of new rose varieties (Wilkes and Williams, 1983).

Methods and Techniques of Germplasm Screening

Germplasm screening for resistance to black spots in roses (*D. rosae*) is essential for identifying and developing cultivars with improved resistance to this common fungal disease (Debener and Byrne, 2014). Black spots weaken roses and cause defoliation that reduces their aesthetic value. Traditionally, there were several ways in which germplasm was screened for resistance of roses to black spot disease (Lopez Arias et al., 2020).

Controlled Inoculation

This inoculation method is conducted using black spot fungus in the rose plants to test various germplasm lines that shows resistance against disease (Debener and Byrne, 2014). Geographic settings limit seedling selection as well as the level of natural field inoculum. These factors affect the breeder's ability to identify and prioritize resistance to pathogens (Debener and Byrne, 2014). Inoculation involves spraying spore suspension on foliage or applying infected leaf material (Cohen and Kuc, 1981). After inoculation, the disease severity is rated at weekly or regular intervals on a standardized 0-to-9 scale for lesions and defoliation, no symptoms to severe symptoms (Hatton et al., 2018). Several observations will give an idea about the development of disease and general resistance of the germplasm (Van Inghelandt et al., 2012).

Genetic Markers

Marker-assisted selection (MAS) identified genetic markers for black spot resistance in roses and thus indirectly allowed for the selection of resistant germplasm (Foolad and Panthee, 2012). The use of MAS requires a prioritization of traits and identification of specific genes based on their importance (Kelly et al., 2003).

Quantitative Trait Loci (QTL) Mapping

Quantitative trait loci (QTL) mapping clarifies the genomic regions in rose harboring genes responsible for resistance to black spot. Further, it develops an understanding of genetic factors and breeding processes (Yan et al., 2007). The paper focuses on the development of molecular markers for use in marker-assisted selection and their inheritance and transmission (Stuber, 1995).

RNA Sequencing (RNA-Seq) and Transcriptome Analysis

RNA-Seq studies gene expression during black spot infection, highlighting resistance mechanisms (Meng et al., 2022). Analysis found up-regulated genes linked to flavonoid, phenylpropanoid, and salicylic acid pathways in resistant varieties (Neu, 2018).

Case Studies of Successful Germplasm Screening

This requires the screening of germplasm to develop resistant rose varieties against the black spot disease caused by *D. rosae* (Debener and Byrne, 2014). The earlier approach included screening germplasm to identify rose cultivars possessing natural resistance within the species itself (Schulz et al., 2009). They tested and screened several rose cultivars for their potential to resist black spot infection using inoculation techniques under controlled conditions (Blechert and Debener, 2005). Natural resistance was bred through breeding programs by using resistant cultivars for the development of new varieties (Horn, 2002). Today, newly developed resistant rose varieties are commercially available and highly prized by gardeners for their stronger resistance to the disease with a lesser need for fungicides (Russell, 2005).

Genomic Analysis for Resistance Genes

Scientists have studied molecular genetics through genomic sequencing and bioinformatics to study the DNA of resistant rose cultivars to black spot disease (Debener, 2019). They sought genes and markers for resistant cultivars by comparing resistant roses with susceptible ones (Whitaker et al., 2010). Genetic information thus allowed breeders to apply MAS for quick detection and screening of new varieties of roses for resistance to black spot, thereby accelerating breeding (Su et al., 2019).

Enhancing Black Spot Resistance through Biotechnology

Genetic engineering is used by scientists in biotechnology to make roses resistant to black spot disease by transferring genes from other plants that are resistant to diseases (Azadi et al., 2016). Genetic engineering helps in breeding flowers by introducing desired genes in ornamental flowers that may not naturally exist in the flowers (Chandler and Brugliera, 2011). Rigorous testing proved that the genetically engineered roses have shown increased resistance against black spots (Rajapakse et al., 2001). These are currently being commercialized for resistant varieties, for use in gardens by growers (Chandler and Tanaka, 2007).

Global Collaboration for Black Spot Resistance

International organizations and research institutions undertook germplasm screening across the globe. Scientists have taken germplasm of different rose regions under diverse climates and presence of black spot disease (Carlier et al., 2002). It was observed, after screening thousands of rose accessions, that there exist genetic variability and resistance components that may be exploited for development of region-specific disease-free rose varieties (Delrot et al., 2020). Hypothetical case studies state that germplasm-screening through the application of breeding techniques and contemporary technologies developed rose varieties, which resistant to black spot disease infection (Wille et al., 2019). This aids in sustaining a healthy rose industry that also equips gardeners to culture healthier and resilient roses (Ellis et al., 1996).

Combining Multiple Resistances for Durable Black Spot Disease Control in Roses

Black spot disease threaten the survival of roses by imposing innovation in control measures (West et al. 2010). With multiple resistance coming as a significant result from such adaptation by the pathogen coupled with limitations in having just a single resistance mechanism, scientists rely on the multiplicity to contain it (Ewen, 2013). With advancements, researchers and breeders have stacked multiple resistance traits in rose cultivars to fight the black spot disease more sustainably (Lopez Arias, 2021). Inspired from success cases of other crops, it integrates different mechanisms of resistance for better durability against black spots (Peace et al., 2019). Gene combinations that offer specific and broad-spectrum resistance enhance the plant's defenses and limit pathogen adaptation (Valkonen, 2015). Advances in breeding and genomics enable the identification and integration of resistance genes from any source. Molecular markers and genetic mapping enable breeders to combine desirable traits precisely.

New tools, like genome editing, allow for the generation of roses with custom resistance, thereby improving the management of diseases (Sikora et al., 2011). It has been associated with deployment of such resistances and genetic compatibility balance as well as resistance level with other traits in roses (Burdon et al., 2014). Field experiments and evaluations establish the feasibility of any resistance strategy. A holistic approach towards disease management, as Thresh and Cooter put forward in 2005 is required. Cultural practices plus biological agents with judicious fungicide use enhance genetic gain, improving black spot management (Pande, 2009). The vision of spotless roses is brought closer by the horticultural and scientific community collaboration (Hayden, 1997). This pursuit of combined resistances promotes a sustainable approach in line with the environmental stewardship and aesthetic goals. "Combining Multiple Resistances for Durable Black Spot Disease Control in Roses" marks a key step to fight the rose pathogen, as proposed by Avrami in (2012). Combining such resistances with proper integrated management practices, we tend to look for healthier and resilient landscapes.

Challenges and Limitations in Germplasm Screening

Germplasm screening for black spot disease resistance is valuable in breeding programs and disease management strategies (Debener and Byrne, 2014). The genetic basis of disease resistance is often complex and involves multiple genes with varying degrees of influence (Halpin et al., 2001). However, Identifying and manipulating of R genes is challenging, primarily if their interactions need to be better understood. Pathogens like *D. rosae* exhibit high levels of genetic variability. Different strains or isolates of the pathogen may interact differently with various germplasm, making it difficult to identify consistent resistance across all strains (McCouch12 et al., 1994). Resistance observed in controlled environments may not always translate to real-world conditions. Environmental factors such as temperature, humidity, and light significantly influence disease development, potentially leading to variations in resistance efficacy (Varanasi et al., 2016). Resistance in germplasm can break down over time due to pathogen evolution (Gayacharan et al., 2020). Pathogens may adapt to overcome plant defenses, potentially rendering previously resistant germplasm susceptible. This highlights the importance of continuously monitoring resistance over generations. Black spot resistance is quantitative (controlled by multiple genes) or qualitative (controlled by single genes) (Crespel et al., 2002). Quantitative resistance may require more complex breeding strategies, while qualitative resistance may be easier to identify but could also be more susceptible to pathogen adaptation (Pilet-Nayel et al., 2017). Several crop species commonly use molecular markers for genetic studies, including constructing linkage maps and mapping qualitative and quantitative traits (Chaparro et al., 1994). In the Rosaceae, maps have, for instance, been developed in Malus, Prunus, and Rosa. Limited sources of naturally resistant germplasm may be available (Kennedy et al., 1987). This scarcity hinders breeding efforts and necessitates seeking alternative resistance mechanisms. Screening many germplasm varieties for resistance requires significant time, resources, and infrastructure. Conducting rigorous evaluations and maintaining disease nurseries is resource-intensive (Fox, 1996). Phenotyping for disease resistance is subjective and prone to variation. Accurate and consistent assessment of disease symptoms requires trained personnel, and even then, variability may exist in interpreting results (Ghosal et al., 2018). Using resistant germplasm or genetically modified organisms (GMOs) raises ethical and environmental concerns among consumers and regulators, impacting the acceptance and adoption of disease-resistant crops (Qaim, 2020). Germplasm screening may center the assessment only on black spot disease and overlook interactions with other pathogens or abiotic stresses that would have a general effect on health of the plant. The employment of resistant germplasm is limited by intellectual property rights and, therefore, restricts the availability of genetic resources to both researchers and breeders. The introduction of genetically modified or gene-edited crops, exhibiting resistance to specific diseases, may require competition with sophisticated legal frameworks (Agapito-Tenfen et al., 2018). Researchers and plant breeders need to make use of novel molecular techniques, holistic approaches, and rigorous testing in the field, including environmental fluctuations. The better the interaction of plants, pathogens, and their environment, the better should one overcome the limits on black spot disease for resistant germplasm screening.

Future Prospects and Research Directions

Germplasm screening in roses toward resistance to black spot is relevant for knowing the mechanisms of this disease and the sustenance of rose culture. Genomic studies, comparative genomics, and transcriptomics explain the molecular background that may underlie black spot resistance in roses, as recently discussed by Song et al. (2024) and Weckwerth et al. (2020). This has unmasked some of the key pathways, genes, and regulators of resistance and has been able to help develop targeted breeding strategies. Validation of candidate resistance genes by knockout, editing, and overexpression reveal their roles and interactions with other genes and factors in resistance (Puschnik et al., 2017). Actually, integration of omics data reveals critical, intricate associations between genes, proteins, and metabolites (Zierer et al., 2015). Systems biology revealed essential networks for resistance to black spot (Rodriguez et al., 2019). Next-generation phenotyping technologies make it possible to rapidly assess disease resistance in large germplasm (Shakoor et al., 2017). Automated image acquisition, remote sensing, and monitoring enhance data capture (Herzig et al., 2021). Studies on epidemiology of black spot disease and *D. rosae* strain interactions are still ongoing. Rose cultivars have proven to be valuable tools for understanding pathogen evolution (Daughtrey and Benson, 2005). Studies of the molecular interaction between pathogen and host may help explain resistance mechanisms. Rose microbiomes have been analyzed for beneficial microbes that support disease resistance (Compant et al., 2019). This microbiome can be modulated to enhance plant health. This approach increases information sharing and cooperation among the researchers in conducting research relating to resistance to black spot. Focus on identifying and stacking multiple resistance genes to achieve durable quantitative resistance against evolving pathogens. Research consumer perceptions of disease-resistant roses, including acceptance of genetically modified or gene-edited varieties. Understanding consumer preferences guiding breeding efforts and market strategies (Caradus, 2022). Examine ethical, environmental, and regulatory aspects of deploying genetically modified or gene-edited roses with black spot resistance traits. Collaboration between researchers, policymakers, and stakeholders is essential. Conduct extensive field trials across diverse environments to validate the effectiveness and durability of resistance traits and multi-site trials are comprehensively assess resistance performance. By embracing these prospects and research directions, germplasm screening for black spot resistance in roses making significant strides toward developing sustainable and robust rose cultivars less susceptible to black spot disease.

CONCLUSION

Throughout this review, we have explored various methodologies and approaches that researchers have developed to identify and cultivate black spot-resistant rose varieties. Our analysis underscores the multifaceted challenge black spots pose and the advancements made in deciphering the genetic, physiological, and molecular factors contributing to resistance. Researchers have displayed remarkable originality in pursuing roses with enhanced resistance traits from traditional field evaluations to cutting-edge genomic analyses. Moreover, integrating data-driven computational tools has emerged as a promising avenue, enabling the rapid identification of candidate genes and markers linked to resistance. No single screening technique can fully address the complexity of black spot resistance. Instead, a complete approach that synergistically combines various strategies appears most promising. Collaborating among multidisciplinary teams becomes dominant as we await further plant science and genomics advancements. Breeders, geneticists, pathologists, and data scientists must collaborate to unravel the intricate interplay between the rose genome and the black spot pathogen.

Furthermore, cutting-edge technologies like gene editing expedite breeding and create roses with targeted resistance traits. Regulatory considerations, ethical implications of genetic modification, and the need to balance resistance with other desirable traits pose significant hurdles **(Figure 3).** Nevertheless, this review underscores that our collective efforts have positioned us closer than ever to a future where the vivid beauty of roses is enjoyed without the constant threat of black spots. In the end, the pursuit of black spot-resistant roses goes beyond aesthetics. It symbolizes our determination to attach scientific innovation to improve our natural environment and sustain agricultural practices.

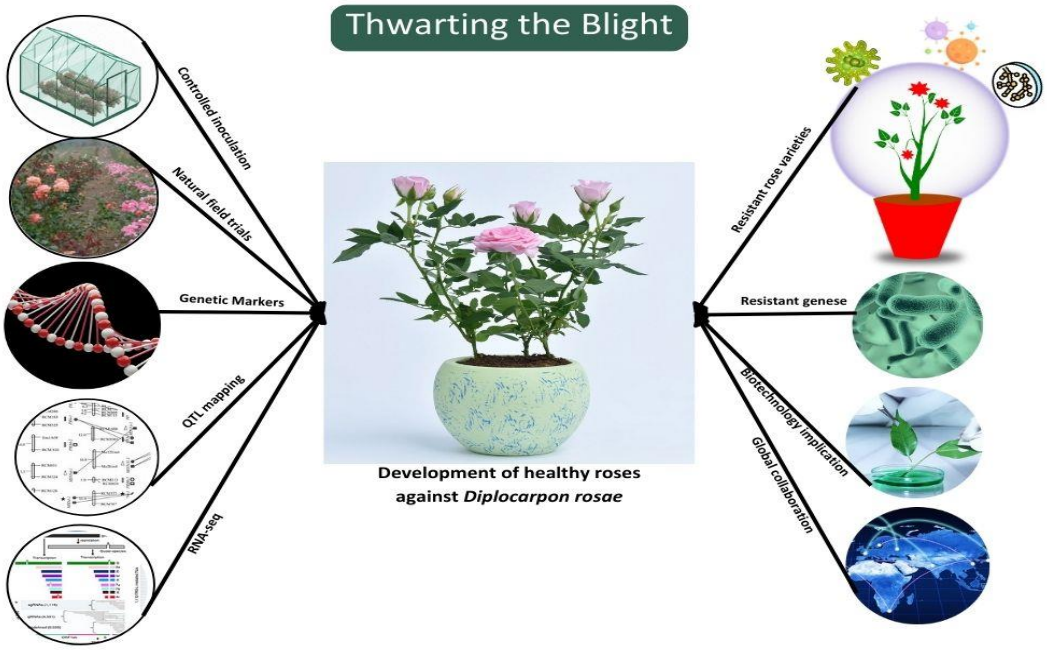

Figure 3: Concluded sketch of all current techniques for the management of Black spot of roses

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Not applicable.

AUTHOR CONTRIBUTIONS

Shahab Ali and Wu Hongzhi concealed the idea. Muhammad Zeeshan Shahid conducted the research trial and collected data. Saira Akhtar performed statistical analysis. Shahab Ali and Owais Iqbal wrote this manuscript of the paper. Li Zhengsheng and Rizwan Khan reviewed the manuscript.

COMPETING OF INTEREST

The author declares no completing of interest.

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