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REVIEW ARTICLE

Effective Strategies for Soybean Disease Control

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ABSTRACT

Soybean (Glycine max L.) cultivation in the United States spans approximately 39.6 million hectares annually, yielding 2.7 to 3.4 tonnes per hectare, contributing over $40 billion annually. Despite their high economic value and versatility, soybeans face significant yield threats from various pathogens, including fungi, bacteria, nematodes, and oomycetes. Diseases such as soybean cyst nematode, charcoal rot, and seedling diseases consistently affect production regions, while others like Phytophthora stem and root rot, sudden death syndrome (SDS), and Sclerotinia stem rot are influenced by environmental conditions. The soybean cyst nematode remains a primary concern, causing substantial economic losses. Effective management strategies encompass genetic resistance, crop rotation, fungicides, biocontrol, and cultural practices tailored to regional conditions. Advancements in bioengineering have enhanced resistance traits, though the emergence of resistant pathogen biotypes presents ongoing challenges. Comprehensive understanding of pathogen biology, disease cycles, and environmental influences is crucial for developing integrated disease management approaches, ensuring sustainable soybean production and economic stability.

Key words: Soybean Diseases, Disease Control Strategies, Cultural Practices, Chemical Control, Crop Rotation

INTRODUCTION

Understanding Soybean Diseases: An Overview

Since the turn of the millennium, soybean (Glycine max L.) cultivation in the United States has maintained an average of 39.6 million hectares (98 million acres) harvested annually, yielding between 2.7 and 3.4 tonnes per hectare (40 and 50 bushels per acre, based on a standard weight of 60 lbs. per bushel of soybeans). This consistent production has translated to an estimated annual value exceeding $40 billion over the past two decades. Globally recognized for its high-quality oil and protein content, soybeans contain approximately 20% oil and 40% protein. While the oils find application in culinary practices and baking, recent environmental initiatives aiming to reduce carbon emissions and fossil fuel dependency have spurred the utilization of soybean oils as biodiesel. Notably, about 70% of the soybean's value is attributed to its meal, primarily utilized in livestock and poultry feed, with additional industrial uses such as adhesives and paints (Lin et al., 2022).

Unfortunately, soybeans are vulnerable to numerous diseases and pests, which can lead to substantial reductions in yield. For instance, between 2010 and 2014, soybean yield experienced an average estimated reduction of 11.5 million tonnes (421 million bushels) nationwide. In 2018 alone, soybean losses due to diseases amounted to 14.6 million tonnes (536 million bushels). These threats emanate from various pathogens spanning fungi, bacteria, nematodes, and oomycetes. While specific threats may vary across regions, certain pathogens consistently pose concerns across both northern and southern production areas. These include the soybean cyst nematode, charcoal rot, and seedling diseases. Conversely, diseases like Phytophthora stem and root rot, sudden death syndrome (SDS), and Sclerotinia stem rot exhibit intermittent threats, influenced by environmental factors. Emerging threats to soybean production encompass root-knot and reniform nematodes, frogeye leaf spot, and Diaporthe diseases (Bandara et al., 2020). The economic ramifications of these diseases have spurred extensive research into their biology,

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epidemiology, and management. The soybean cyst nematode remains a predominant and consistent threat, with nearly 977 peer-reviewed publications in the past two decades. Similarly, the gene-for-gene relationship between soybeans and Phytophthora sojae has catalyzed significant research efforts. Despite the significant yield threat posed by diseases like charcoal rot, they have received comparatively less research attention. Disease management strategies in row-crop agriculture typically involve genetic resistance, crop rotation, seed treatments, fungicide sprays, and biocontrol methods. Additionally, cultural practices such as tillage modifications, row spacing adjustments, plant population management, and irrigation can contribute to disease reduction. Given the regional environmental variations, the effectiveness of these strategies may vary, necessitating tailored approaches for each disease (Shea et al., 2020; Zafar et al., 2020).

Being among the pioneering bioengineered crops to achieve commercial viability, soybeans have gained significant traction among producers due to reduced production costs. However, existing prohibitions against bioengineered soybeans in regions like Europe and Japan pose potential challenges for producers regarding resource utilization, marketing strategies, and international trade. While initial efforts primarily focused on traits aimed at cost reduction, such as herbicide resistance, future developments are expected to introduce enhanced functionalities like pest resistance, high oleic content, high stearate content, and increased omega-3 levels. Currently, 94% of soybeans grown in the United States are bioengineered, while the figures stand at 89% and 100% for Brazil and Argentina, respectively. Soybeans dominate the oilseed crop market, constituting 57% of global production. Primarily cultivated for their oil (about 19%) and protein (about 40%) content, soybeans provide a complete protein source, containing significant amounts of all essential amino acids required by humans. Soybean processing yields a diverse range of products including adhesives, cosmetics, paints, plastics, textile fibers, salad dressings, meat substitutes, infant formulas, and pet foods (Hu et al., 2020).

Advancements in management practices, encompassing improved seed varieties, fertilizer usage, and pesticide applications, have led to the development of disease-resistant varieties, thereby increasing yields and encouraging soybean acreage expansion in the U.S. Nonetheless, viral infections continue to pose significant threats to producers, causing substantial losses. In 2010, virus-induced losses in the U.S. were estimated at approximately $35 million, although this figure might be conservative given the latent nature of many viruses. Effective disease management practices include mitigating seed transmission, avoiding planting near alternative virus hosts, deploying resistance genes, and employing insecticides to reduce virus vector populations (Ma et al., 2020). A multitude of viruses capable of infecting soybeans have been identified, either naturally occurring or through laboratory inoculation. Soybean diseases pose significant challenges to crop productivity worldwide. This section provides a comprehensive overview, delving into the identification and characteristics of common soybean pathogens, understanding the disease cycle, exploring factors influencing pathogen spread, examining the impact of diseases on crop yields, and analyzing geographical variations in soybean disease patterns (Ejaz et al., 2022; Gul et al., 2014).

Common Soybean Pathogens: Identification and Characteristics

Soybeans encounter a range of pathogens that can threaten their health and yield. Fungi, bacteria, viruses, and nematodes are among the culprits (Hartman & Hill, 2010). Recognizing these pathogens is crucial for effective disease management. The identification involves understanding the morphological features, symptoms they induce, and the specific conditions conducive to their growth. Common soybean pathogens include Fusarium species causing wilt, Phytophthora sojae responsible for root rot, and Soybean mosaic virus leading to mosaic symptoms (Rana & Yousaf, 1988). Each pathogen has unique characteristics, including its preferred environmental conditions, modes of transmission, and the type of damage it inflicts on soybean plants. A detailed understanding of these characteristics is vital for implementing targeted control measures (Hill & Whitham, 2014).

The soybean cyst nematode, scientifically known as Heterodera glycines Ichinohe (Tylenchida: Heteroderidae), stands as the primary menace to soybean yields across the United States. Over the span from 2006 to 2014, this nematode consistently ranked as the foremost economic pest in both northern and southern states, resulting in an annual average yield loss surpassing 3.4 million tonnes (125 million bushels). Given an average market value of soybeans at $330 per tonne ($9 per bushel) between 2000 and 2020, these losses translated to an estimated economic impact exceeding $1.1 billion. The soybean cyst nematode is an obligatory, plant-parasitic organism thriving in various soil types and geographical regions. With a life cycle spanning 3 to 4 weeks on a susceptible host, it undergoes multiple generations within a single season, leading to a significant surge in nematode population density (Tariq et al., 2020). Foliar symptoms linked to soybean cyst nematode infestation are often confused with nutrient deficiencies, and in many instances, aboveground symptoms may be absent despite substantial yield losses caused by the nematode. Overwintering as eggs enclosed within a cyst (dead female), the nematode can endure adverse soil conditions for a decade or more. Favorable environmental conditions trigger the hatching of eggs, releasing second-stage juveniles (J2) in search of soybean roots. Optimal hatching conditions include warm soil temperatures ranging from 24 to 32°C (75 to 90°F) and sufficient soil moisture, with root exudates further stimulating egg hatch rates. The J2, the sole infective stage, navigates through the soil via water films until encountering a host root. It then penetrates the root, migrates toward the vascular system, and establishes a feeding site known as a syncytium. Subsequent development stages (J3 and J4) occur within the syncytium before molting into adult male or female nematodes. While adult females remain sedentary, enlarging and eventually rupturing through the root epidermis to lay eggs, adult males return to the soil to mate. Females can yield several hundred eggs, primarily retained within the body, with additional eggs deposited in an external gelatinous matrix called an egg mass (Bueno et al., 2021). The resilience of soybean cyst nematode cysts and eggs, capable of surviving without a suitable host for over a decade, presents challenges in predicting the impact of extreme weather events. Even juveniles can endure extended periods in flooded or dry soil conditions. However, as global temperatures are anticipated to rise, facilitating increased rates of nematode reproduction and egg hatching, the nematode's prevalence and impact are likely to escalate. Temperature fluctuations, though, could also impede soybean germination, leading to a complex interplay of factors influencing soybean yield. Projected temperature increases might encourage soybean cultivation in traditionally non-cultivated northern areas, yet they could also exacerbate soybean cyst nematode problems in southern states and spread its prevalence to northern regions. This scenario portends potential declines in soybean yields across the United States (Karlekar & Seal, 2020).

Charcoal Rot

Charcoal rot, caused by the fungus Macrophomina phaseolina, is a destructive disease affecting a wide range of crops, including soybeans. It is prevalent in warm and dry climates, making it a significant concern for soybean producers in regions with such environmental conditions. The disease poses considerable economic threats due to its ability to reduce crop yields and seed quality. Charcoal rot can have devastating consequences on soybean yield and quality. The fungus infects plants through the roots, leading to symptoms such as wilting, leaf scorching, and premature plant death, particularly during periods of stress, such as drought. The pathogen colonizes the vascular system of the plant, causing blockages that impede water and nutrient transport, exacerbating the symptoms (He et al., 2021). One of the distinguishing features of charcoal rot is the production of small, black sclerotia within the plant tissues, giving infected stems a characteristic blackened appearance. These sclerotia can survive in the soil for several years, serving as a source of inoculum for subsequent plantings, perpetuating the disease cycle. The economic impact of charcoal rot extends beyond yield losses. Infected seeds can exhibit reduced germination rates and seedling vigor, affecting stand establishment and overall crop performance. Additionally, charcoal rot-infected seeds may have reduced market value due to lower quality and increased susceptibility to secondary pathogens. The disease cycle of charcoal rot begins with the presence of Macrophomina phaseolina in the soil, either as sclerotia or mycelia (Cai et al., 2021). The fungus can survive for extended periods in crop residues, soil, and alternative hosts. Under favorable conditions, such as warm temperatures and low soil moisture, the sclerotia germinate, producing hyphae that infect susceptible host plants. Upon infection, the fungus colonizes the root cortex, eventually spreading to the vascular tissues. As the fungus grows within the plant, it produces hyphae and sclerotia, which further colonize the host tissues. The formation of sclerotia within the plant tissues contributes to the characteristic blackening observed in infected stems. As infected plants wilt and die, the fungus produces abundant sclerotia, which are released into the soil upon plant decomposition. These sclerotia serve as a source of inoculum for future plantings, perpetuating the disease cycle. Additionally, sclerotia can be spread via contaminated farm equipment, irrigation water, and wind, facilitating the dissemination of the pathogen within and between fields (Oliveira et al., 2024).

Management strategies for charcoal rot typically focus on cultural practices, such as crop rotation, residue management, and irrigation management, aimed at reducing pathogen inoculum levels in the soil and minimizing stress conditions conducive to disease development. Additionally, genetic resistance and fungicide applications may be employed to supplement cultural control measures, providing integrated approaches to effectively manage charcoal rot and minimize its impact on soybean production (Kamal et al., 2024).

Disease Cycle and Factors Influencing Pathogen Spread

The disease cycle is a fundamental aspect of understanding soybean diseases. It encompasses the sequence of events from the introduction of the pathogen to its reproduction and the subsequent infection of new hosts. The cycle varies among pathogens, but typically involves stages like penetration, colonization, and dispersal. External factors, such as temperature, humidity, and host susceptibility, play pivotal roles in determining the pace and intensity of the disease cycle (Sikora et al., 2014). Factors influencing the spread of soybean pathogens are multifaceted. Environmental conditions, cultural practices, and the presence of alternative hosts contribute to the dissemination of diseases (Kalaitzandonakes et al., 2019). Weather patterns, especially during critical growth stages, can either exacerbate or mitigate disease outbreaks. The interplay of these factors requires a holistic approach in disease management strategies (Roth et al., 2020).

Impact of Soybean Diseases on Crop Yields

Soybean diseases can have profound effects on crop yields, directly impacting agricultural economies and food security. Yield losses are often a result of reduced photosynthesis, nutrient uptake, and overall plant vigor caused by diseases (Willbur et al., 2019). Some pathogens lead to premature senescence, pod abortion, or seed quality deterioration.The economic ramifications extend beyond the immediate crop. Yield losses contribute to increased production costs, as farmers may need to invest in additional inputs for disease control. Furthermore, market value can be compromised due to lower-quality soybeans. Understanding the specific mechanisms through which diseases affect crop yields is essential for developing effective management strategies (Juliatti et al., 2017).

Geographical Variations in Soybean Disease Patterns

Soybean diseases exhibit geographical variations influenced by climate, soil conditions, and agricultural practices. Certain diseases thrive in specific regions due to the prevalence of conducive environments. For example, areas with high humidity may experience a higher incidence of fungal diseases like rusts and leaf spots, while bacterial diseases might be more prevalent in regions with warm temperatures (Kalaitzandonakes et al., 2019). Geographical variations also extend to the distribution of different soybean cultivars. Some varieties show resistance or tolerance to specific diseases, making them more suitable for cultivation in particular regions. Understanding these variations allows farmers to tailor disease management strategies based on the prevalent pathogens in their specific geographical area (Sikora et al., 2014; Tarar et al., 2022). Identifying common soybean pathogens, understanding the disease cycle and factors influencing pathogen spread, recognizing the impact of diseases on crop yields, and considering geographical variations in disease patterns collectively provide a holistic perspective (Rana & Yousaf, 1988). This knowledge forms the basis for developing targeted and sustainable strategies to mitigate the impact of soybean diseases and ensure the resilience of soybean cultivation worldwide.

Implementing Effective Disease Control Strategies

Soybean diseases necessitate a proactive and multifaceted approach to safeguard crop health and ensure optimal yields. This section explores various strategies for effective disease control, encompassing Integrated Pest Management (IPM), the utilization of resistant varieties, cultural practices for prevention and control, and the judicious role of chemical control in managing soybean diseases (Raza et al., 2021; Roth et al., 2020).

Integrated Pest Management (IPM) in Soybean Cultivation

Integrated Pest Management (IPM) is a comprehensive strategy that harmonizes various pest control methods to minimize the impact on the environment while ensuring effective disease management in soybean cultivation. IPM involves the judicious use of biological controls, cultural practices, and chemical interventions. Regular monitoring of pest populations and disease incidence aids in timely decision-making, preventing the escalation of problems. Biological controls within an IPM framework include the introduction of natural predators, parasites, and pathogens that target soybean pests. This ecological approach helps maintain a balance between pests and their natural enemies, reducing the reliance on chemical interventions. IPM also emphasizes the importance of cultural practices and crop rotation to disrupt the life cycle of pathogens, contributing to long-term disease control (Mukhtar & Ahmed; Muzammal et al., 2014).

Genetic Resistance for Soybean Disease Resistance

Genetic resistance stands out as the primary and most effective approach for managing soybean cyst nematode (SCN). The predominant source of genetic resistance in commercial soybean lines can be traced back to the plant introduction line PI88788. Although alternative SCN resistance genes exist in various soybean breeding lines, PI88788 remains the predominant reservoir of resistance. This resistance is typically quantitative, with mechanisms and causal genes not fully elucidated. The resistance in PI88788 is attributed to a quantitative trait locus (QTLs) situated on chromosome 18, known as Resistance to Heterodera glycines 1 (Rhg1). Intriguingly, the Rhg1 locus in PI88788 harbors numerous copies of three unrelated genes, whereas susceptible varieties possess fewer copies of these genes (Widyasari et al., 2020). Additional QTLs associated with SCN resistance have been identified, some overlapping with QTLs linked to resistance against other significant soybean diseases. The continuous identification of QTLs associated with robust SCN resistance remains a crucial research avenue, given the significant selection pressure exerted by repeated planting of cultivars with PI88788 resistance. In fact, the repetitive planting of any resistant cultivar can drive SCN populations to adapt and overcome resistance. Recent genome sequencing efforts of multiple SCN populations have provided valuable insights into the mechanisms of SCN virulence. Collaborative initiatives have resulted in the development of an open-access SCN genome browser, facilitating timely discoveries of genetic mechanisms underlying soybean resistance to detrimental pests and pathogens (Haq & Ijaz, 2020). The evolving ability of

SCN to surmount genetic resistance has led to the emergence of distinct biotypes or races. The HG typing system has been devised to classify these biotypes based on their ability to reproduce on soybeans containing known sources of resistance. This system aids farmers in identifying the SCN populations they encounter and selecting genetically resistant cultivars tailored to manage SCN in their fields. Studies have demonstrated that selecting cultivars based on this system confers significant yield advantages, particularly with early-maturing soybean cultivars (Rahman et al., 2023).

Resistant Varieties: Building a Defense against Pathogens

Breeding soybean varieties with inherent resistance to specific pathogens is a powerful strategy for disease control. Resistant varieties serve as a frontline defense, mitigating the need for extensive chemical treatments. Plant breeders employ various techniques, including conventional breeding and genetic engineering, to develop cultivars with resistance genes. Resistant varieties not only provide a direct defense against pathogens but also contribute to overall sustainability by reducing the environmental impact of chemical applications. Farmers can select cultivars tailored to their specific geographical region, considering prevalent disease pressures. Ongoing research and development efforts continue to enhance the range and durability of resistance traits in soybean varieties (Pandit et al., 2020).

Cultural Practices for Disease Prevention and Control

Cultural practices play a pivotal role in preventing and controlling soybean diseases, contributing to sustainable and environmentally friendly disease management strategies. Crop rotation is a cornerstone, disrupting the disease cycle by introducing non-host crops in the rotation (Juliatti et al., 2017). This practice reduces the buildup of pathogens specific to soybeans, mitigating the risk of disease carryover between seasons. Additionally, conservation tillage practices help in residue management, controlling the potential sources of disease inoculum (Shaibu et al. 2020). Proper sanitation, including the removal and destruction of infected plant debris, is crucial to minimize the reservoirs for pathogens and prevent disease spread. These cultural practices collectively contribute to breaking the chain of infection, fostering healthier soybean crops and enhancing long-term disease resistance (Khan & Khaliq, 2004).

Role of Chemical Control in Managing Soybean Diseases

The judicious use of chemical control remains a key component in managing soybean diseases effectively. Fungicides and bactericides are strategically applied when disease pressures reach critical levels that could lead to significant yield losses (Iqbal et al., 2019). This preventive approach is especially crucial during critical growth stages or under weather conditions conducive to disease development. The choice of chemical agents is tailored to the specific pathogens present, considering their susceptibility to different compounds. Integrated with other control strategies, chemical control provides a targeted and efficient means of curbing disease progression, ensuring a balanced approach that optimizes efficacy while minimizing the environmental impact. The goal is to strike a careful balance between effective disease management and sustainable agricultural practices, safeguarding soybean crops while preserving the overall health of the agroecosystem (Hussain et al., 2011; Iqbal et al., 2021).

Chemical control of nematodes and other soilborne pathogens poses challenges due to the difficulty in timing and delivering the chemistry into the soil, along with potential adverse effects on beneficial soil microbes. However, advancements in agricultural chemistry have yielded new formulations with increased specificity toward target pathogens, often requiring lower rates of active ingredients for effective control. Many of these chemistries are now available as seed treatments, ensuring direct delivery into the soil alongside the seed, reducing the required active ingredient rates and precisely targeting where it is needed while safeguarding germinating seedlings (Tripathi et al., 2022).

Several common chemistries are employed to manage soybean cyst nematode (SCN), including abamectin, fluopyram, pydiflumetofen, and tioxazafen. Abamectin, a natural compound derived from the bacterium Streptomyces avermitilis, disrupts neuron signaling in nematodes and arthropods, proving effective against SCN. Fluopyram, classified as a succinate dehydrogenase inhibitor (SDHI), impacts cellular respiration and has demonstrated efficacy against SCN and fungal pathogens in field studies, reducing nematode numbers in roots and inhibiting reproduction in soybean varieties. Laboratory studies have shown that fluopyram also impairs nematode motility and prevents root penetration. Pydiflumetofen and tioxazafen are newer chemistries registered for use as nematicide seed treatments in soybeans, although comprehensive efficacy comparisons with other products are not yet widely available (Roth et al., 2020).

Biological control strategies harness certain microbes that either compete with SCN for soybean root associations or directly parasitize them. Commercially formulated seed treatments containing specific strains of these microbes offer promising avenues for SCN management. Products such as Votivo, Clariva pn, Aveo EZ Nematicide, BIOST Nematicide 100, and Trunemco incorporate beneficial microbes to control nematode populations. Although the fungus Hirsutella rhossiliensis exhibits parasitic activity against SCN juveniles, its commercialization or widespread use as a biocontrol agent remains limited. Recent research highlights the potential of certain fungi present in soybean and corn roots to release compounds toxic to SCN, with crop rotation and nematode density influencing fungal communities on soybean roots, thereby offering additional avenues for biological control (Li et al., 2020).

Conclusion

In conclusion, a holistic approach to soybean disease management is vital for sustaining crop health and optimizing yields. By integrating cultural practices, utilizing resistant varieties, implementing IPM strategies, and judiciously employing chemical control, farmers can foster resilient soybean crops while minimizing environmental impact. This review underscores the significance of adaptable, sustainable practices in soybean agriculture.

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