Nematode Management Strategies for Sustainable Agriculture and Healthy Soil Ecosystems: A Mini Review

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Abstract

Sustainable agriculture relies on improving crop yields for a growing world population, while mitigating the negative pressures by plant pathogens on soil health and crop yield. Plant pathogens involve a wide range of fungi, bacteria, and microscopic worms (or nematodes). Several foodgrain crops incur significant yield losses because of nematode infestations. Nematodes make their way to the roots of growing plants, developing feeding sites, and completing their life cycle which gradually compromises the health and yield of the plant. As such, nematode management strategies are vital to sustainable agriculture. Unfortunately, nematodes have outsmarted and adapted to the conventional control strategies, including both chemical and biological control strategies. It is important to develop a comprehensive, robust, and multifaceted approach that is effective in the prevention, surveillance, early detection, and rapid response of nematodes. To take our society towards a resilient, sustainable agrifood system, we need to actively prioritize and invest our resources in nematode disease management, build capacity of farmers and researchers, and develop robust nematode management strategies that can withstand the challenges of the future. The goal of this mini review is to summarize these abovementioned topics of active research in nematode management for sustainable food security.

Introduction

Nematodes are soil-dwelling organisms, many of which are parasitic in nature causing significant harm to crop and leading to substantial yield losses [1-4]. As such, parasitic nematodes are recognized as major contributors to foodgrain crop damage, posing significant threats to achieving the sustainability goals of global food security. Nematology research plays an important role in addressing this global challenge and safeguarding food supplies for sustainable agriculture. Investment in nematology research is essential to advance food security objectives, encompassing the identification and management of nematode species, the development of innovative technologies, understanding nematode ecology, and strengthening the capacity of researchers and farmers [4-10]. This effort is vital in tackling one of the most urgent challenges in achieving global food security and fostering sustainable agricultural practices.

As the global population steadily increases towards ten billion by 2050, it is imperative to ensure food security while mitigating the adverse impacts of food production on ecosystems. One of the major challenges is the prevalence of plant diseases. These plant diseases pose a significant threat, capable of ravaging crop yields, compromising produce quality and marketability, and jeopardizing the livelihoods of farmers and food producers. All major crop (e.g., grains, fruits, vegetables, or cash crops) is immune to the effects of plant diseases, which can swiftly spread across regions and continents [1-10].

Plant diseases are a significant challenge in countries where smallholder farmers rely heavily on agriculture for sustenance, as plant diseases can exacerbate poverty and food insecurity by diminishing crop yields, escalating input costs, and limiting market access for farmers [11-17]. The development and implementation of effective plant disease management strategies are imperative to promote food security and ensure sustainable agricultural intensification [14-20]. It is important to develop a comprehensive, robust, and multifaceted approach that encompasses prevention, surveillance, early detection, rapid response, and ongoing research and development. By prioritizing and investing in plant disease management, we can establish a resilient, sustainable food system capable of withstanding the challenges of the future, thereby guaranteeing nourishment and security for all.

Plant Pathogens and Threat to Soil Sustainability

Fungi, bacteria, viruses, and nematodes represent common plant pathogens capable of inflicting considerable damage to crops, thereby impacting food security [20-31]. Among these, nematodes stand out as particularly detrimental to crop health. Plant-parasitic nematodes, microscopic worm-like organisms residing in the soil, feed on plant roots, resulting in stunted growth, diminished yields, and, in severe cases, plant fatality. The agricultural sector faces significant challenges from nematodes due to their capacity for causing substantial crop damage, leading to reduced yields and financial losses for farmers. Their wide host range and prolonged soil persistence render nematodes challenging to manage effectively. Nematology research assumes a critical role in identifying and managing nematode species, developing innovative technologies, comprehending nematode ecology, and enhancing the capabilities of researchers and farmers [22-27]. Effective nematode management entails employing various techniques, including resistant crop varieties, cultural practices, biological control, and chemical intervention [29-35]. Emerging technologies such as gene editing and beneficial microbes hold promise for conferring resistance to nematode infestations. Understanding nematode ecology is paramount for devising precise and efficacious management strategies. Investigations into nematode behavior and interactions with other organisms and environmental factors yield valuable insights into nematode ecology. Investing in nematology research can foster sustainable agricultural practices and bolster global food security.

Nematode infestations pose a significant threat to crop health, causing extensive damage by feeding on roots, which results in stunted growth, wilting, and diminished yields [1-7]. Such damage leads to notable reductions in agricultural productivity, translating to financial losses for farmers. Additionally, nematode-induced crop damage can render plants more vulnerable to other diseases, compounding the losses. The economic ramifications of diseases caused by nematodes are profound for global agriculture, with plant parasitic nematodes alone causing billions of dollars in annual losses worldwide. These losses stem from various factors, including direct crop damage, yield reduction, and heightened production costs. Besides, nematode infestations necessitate costly management strategies, such as chemical controls, adding financial strain, particularly on farmers in developing nations with limited resources. The consequences extend beyond financial aspects, impacting food availability, market stability, and export revenues, with far-reaching socio-economic implications. In sum, diseases attributed to nematodes incur substantial economic losses annually, emphasizing the critical need for nematology research investment to develop effective management strategies, promote sustainable agriculture, and bolster global food security.

Nematode Management Research for Global Food Security

Nematode management research activities aim at identifying nematode species responsible for crop damage, leading to the formulation of effective management strategies. These strategies include deploying resistant crop varieties, implementing cultural practices, utilizing biological control methods, and employing chemical interventions [33-45]. Additionally, research contributes to the development of novel technologies for managing nematode populations, such as gene editing techniques that confer resistance to nematode infestations in crops. Exploring beneficial microbes, such as certain fungi and bacteria, as potential biocontrol agents against nematodes shows promise. Additionally, the study of nematode ecology serves as a foundational research area that enhances understanding of nematode biology and ecological interactions [12-23]. This knowledge is crucial for devising precise and effective management strategies tailored to specific environments and crop systems. Overall, nematology research plays a vital role in addressing the complex challenges posed by nematode-induced crop damage, ultimately contributing to global food security and the promotion of sustainable agricultural practices.

The contribution of nematology research to the pursuit of global food security is often underestimated. Nematology research serves as a cornerstone in addressing the challenges posed by nematode infestations, offering a multifaceted approach to mitigate their impact on crop yields and enhance sustainable agricultural practices [32-37]. Nematology research aids in pinpointing nematode species responsible for crop damage and devising tailored management strategies. These strategies encompass the deployment of resistant crop varieties, cultural practices, biological controls, and chemical interventions. Implementing such targeted approaches can effectively curtail the economic repercussions of nematode infestations on crop yields while fostering sustainable agricultural practices. Moreover, delving into nematode ecology is paramount, as it furnishes valuable insights into their biology and ecological interactions. By unraveling the intricacies of nematode ecology, researchers can develop nuanced and effective management strategies. These strategies not only mitigate the economic impact of nematode infestations but also promote the long-term sustainability of agricultural practices. Nematology research plays a pivotal role in bolstering the expertise of researchers and farmers in the field. This encompasses training in nematode identification, management strategies, and the utilization of emerging technologies. Strengthening the capacity of stakeholders in nematology fosters the adoption of sustainable agricultural practices and contributes to long-term food security initiatives.

Understanding Nematode Ecology and Phenotypes

Understanding nematode ecology is paramount to deciphering their behavior, distribution, and interactions within the soil ecosystem. Research in nematode ecology delves into the biotic and abiotic factors influencing nematode populations, such as temperature, moisture, soil composition, and plant diversity. This understanding enables the development of targeted management approaches that exploit nematodes' vulnerabilities while minimizing their impact on crops. Moreover, nematode ecology research is instrumental in fostering sustainable agricultural practices. By elucidating the ecological dynamics between nematodes, plants, and other soil organisms, integrated pest management strategies can be devised, reducing reliance on chemical pesticides and promoting natural pest control methods. Furthermore, nematode ecology research drives innovation in nematode management technologies. Insights into nematode genetics and plant-root interactions inform the development of gene-editing tools, enabling the creation of nematode-resistant crops. Therefore, nematode ecology research serves as a foundational pillar informing the development of precise management strategies, fostering sustainable agriculture, and driving the advancement of novel nematode management technologies.

Crop Rotation and Deep Tillage as Sustainable Farm Solutions

Crop rotation stands out as one of the most effective cultural practices for managing nematode infestations [9-22]. This technique involves alternating the planting of susceptible crops with those resistant to nematodes. By doing so, farmers disrupt the nematode life cycle, thereby reducing their populations and preventing soil buildup. The premise behind crop rotation lies in the varying susceptibility of different crops to nematodes. By depriving nematodes of their preferred hosts through rotation, their populations naturally decline. Moreover, besides mitigating nematode populations, crop rotation can enhance soil health, fertility, and structure, resulting in improved crop growth and yields [22-30].

However, the economic viability of rotation crops is crucial for farmers. Rotation crops should not only resist nematode infestations but also be profitable, contributing to the farm's overall income. The yield increase in subsequent crops after rotation should justify the use of land for rotation crops. Therefore, careful selection of rotation crops that are both nematode-resistant and economically viable is imperative.

It's important to note that the manifestation and population levels of plant-parasitic nematodes fluctuate based on the crop grown. Hence, regular sampling is essential to understand the dynamics of different nematode species in a field [6-10]. Effective weed management is also vital to prevent nematode increases on weed host plants. In some scenarios, a combination of cultural practices like crop rotation and cover cropping may be necessary for effective nematode management while maintaining farm profitability.

Additionally, soil management practices such as deep tillage can help reduce nematode populations by exposing them to adverse conditions [11-19]. However, deep tillage may negatively impact soil health, leading to erosion, loss of organic matter, and disruption of soil structure. Therefore, careful consideration of the potential benefits and drawbacks of deep tillage is necessary before its implementation as a nematode management strategy. Reduced tillage or no-till practices may be more suitable alternatives for maintaining soil health while managing nematode populations effectively.

Chemical and Biological Control of Nematodes as Sustainable Farm Solutions

Chemical control stands as a widely employed strategy in agriculture to combat nematode infestations, owing to its immediate impact on nematode populations [21-29]. Nematicides, chemical formulations specifically designed to eradicate nematodes, find extensive use in crops where other management techniques may not suffice or prove effective against nematode infestations. They can be administered to the soil or applied to plant roots to diminish nematode populations and mitigate crop damage. Often, chemical control is employed alongside other management approaches, like crop rotation and resistant crop varieties, to enhance effectiveness and minimize environmental repercussions.

Nematicides typically fall into two categories based on their mode of action: contact nematicides and systemic nematicides [30-42]. Contact nematicides operate by directly encountering nematodes in the soil, swiftly eliminating them upon contact. They tend to be less hazardous than systemic nematicides and exhibit shorter residual effects. Conversely, systemic nematicides are absorbed by plant roots and distributed throughout the plant, rendering them highly potent. However, they may have longer residual effects and higher toxicity levels. While chemical control can prove effective against nematodes in agriculture, it should be employed judiciously and alongside other strategies to mitigate environmental impact and minimize the development of resistance.

Exploring alternative, more sustainable control methods, such as biological control, is imperative for advancing nematology and fostering sustainable agricultural practices [40-45]. Research in this realm is crucial for developing innovative approaches to nematode management while reducing reliance on chemical interventions. Biological control emerges as a sustainable and environmentally conscious method for managing nematodes, reducing reliance on chemical interventions, and fostering beneficial soil organisms. By harnessing such technologies, researchers can alleviate the adverse effects of nematode infestations on crop yields, thereby enhancing food security. Beneficial microbes represent a potential avenue for nematode control. Biological control entails leveraging natural enemies like fungi, bacteria, and other organisms to regulate nematode populations. One example is the utilization of nematophagous fungi, which infect and kill nematodes. These fungi, traditionally classified based on their attacking mechanisms, offer advantages over bacteria and viruses in combating plant-parasitic nematodes.

Another strategy involves employing nematode-trapping fungi as biological control agents, showing promising results against nematodes [31-42]. Additionally, plant-parasitic nematodes can be used to infect and eliminate other nematode species. Biological control may also entail beneficial microorganisms like rhizobacteria, which colonize plant roots, bolster plant growth, induce resistance, and outcompete nematodes for resources, thus reducing their populations. However, the effectiveness of biological control hinges on various factors and necessitates integration with other management approaches for long-term success [40-45].

Conclusion

A global concern is food insecurity caused by plant parasitic pathogens and nematodes pose significant threats to agriculture, particularly in developing and underdeveloped countries where there is lack of awareness about nematode management strategies. Given their potential to incur substantial crop damage and economic losses, understanding and characterizing the phenotypes and behavior of plant parasitic nematodes is the essential first step for devising effective and sustainable control strategies. Nematology experts play a pivotal role in advancing our understanding of nematodes, developing new management strategies, generating ecological knowledge, and building research capacity. Investing in nematology research holds the key to ensuring food security for millions worldwide, especially when traditional strategies are getting outdated and outsmarted in nematode management. While assessing the impact of nematode infestations on crop yields presents significant challenges, sustained research and development efforts by public and private partnerships can bolster our knowledge and innovation in nematode management. Nematology researchers are poised to address this challenge, driving research and development initiatives to safeguard food security and combat plant-parasitic nematodes effectively. Thus, prioritizing nematology research is paramount for achieving global food security and promoting sustainable agricultural practices.

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