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The most important diseases caused by fungi in tomato seeds: A review

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Abstract

Worldwide agriculture productivity and the economy are negatively impacted by plant diseases carried on by several microorganisms that are either present in the soil, seeds, or propagative planting materials, or that are conveyed by the air or water. This review provides a wealth of information about the importance and frequency of different types of seed-borne mycoflora such as *Fusarium* spp., *Alternaria* spp., *Rhizopus* spp., *Aspergillus* spp., *Penicillium* spp., *Colletotrichum* spp. which is specifically linked to tomato seeds. These mycoflora cause devastating tomato diseases such as grey mold, fruit and root rots, Fusarium wilt, early blight, and foot rots, and evaluate a variety of contemporary and traditional methods that are used to identify seed-borne fungi and to implement various control measures, such as chemical and biological approaches that scientists have chosen. Many variables, such as the presence of vulnerable plants, ideal environmental circumstances, and overhead watering, pose significant barriers to the spread of plant diseases. In these circumstances, an efficient disease management strategy consists of monitoring plant health and detecting diseases, especially by screening infested seed lots before planting with the use of seed detection assays.

Keywords: Seed-Borne Fungi; Seed Treatments; Tomatoes; Fungal diseases; Diseases management strategies**.**

1. Introduction

Considering that the main causes of losses in agriculture are fungal diseases, which are exacerbated when they occur in seeds, it was decided to carry out this review to expose the most important fungi that cause diseases in tomato seeds and to communicate the information that can publicize and help fight these diseases (Różewicz *et al*., 2021). Tomato is a very important horticultural crop because of its economic and nutritional value; it is the basis of the diet in many countries. In various parts of the world, there are serious diseases and pests affecting tomatoes, where tomato seeds and seedlings are infected by various factors such as bacteria, fungi, and viruses. Fungi causing diseases in tomatoes lead to significant seed damage, mostly reported to attack fruit, but they can also damage seeds during production (Pandey *et al*., 2022). Farmers in many countries do not recognize most of the pathogenic fungi in tomato seeds and seedlings, which can cause substantial damage (Gyasi *et al*., 2020; Opoku *et al*., 2021). Understanding how fungal pathogens affect tomato production is critical to developing effective disease management strategies. Seeds from disease-free fields of production do not harbor fungus or diseases if properly treated and do not come into touch with external fungal contamination. However, they can be contaminated during seed production, harvesting, processing, shipment, and storage (Barriga & Fiala, 2020). Infection of tomatoes with fungi can be latent, and infected seeds can be derived from healthy plants. It is important to mention that seeds are the main source of infection for many important agronomic and horticultural crops, some of which can cause severe damage early (Johnston-Monje *et al*., 2021; Jones, 2021).

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2. Importance of Tomato Seeds in Agriculture

One of the most significant vegetable crops in the world, tomatoes contribute significantly to human nutrition, support a multimillion dollar business, and are essential to the global food security plan. Due to their tremendous biological value, high-quality tomato seeds play a critical role in modern agriculture by dispensing high regular yields and pest- and disease-resistant healthy plants. People in developing countries normally have a small plot and are completely dependent on tomato seeds for vegetable growing or for subsistence agriculture. Consequently, poor quality tomato seeds extinguish such a major livelihood activity. Moreover, despite their evolutionary significance, tomatoes produce fertile seeds, grandchildren, or furtherance of crop plants, transferring the diversity that farmers, breeders, and conservators have created or released over space and time (Kumar *et al*., 2020; Rivarez *et al*., 2021). This signifies the camaraderie and connection of tomato seeds with people's biological existence. Therefore, smallholder tomato farmers have always relied on safe and good quality seeds for growing crops and their consequences on the sustenance of other farming activities. In recent times, large-scale degraded tomato seed is thought to curtail the genetic speed of evolution caused by several variant stresses. In these situations, after the seeds bear suitable adaptive qualities, such as resistance to a particular pest and high yield, they might be able to be borrowed to propagate plants that deserve to be conserved. Tomato seed selection must therefore be conducive under many conditions since climate adaptation is crucial in coping with adverse weather conditions. Several disappointments of tomato seeds, such as fungal or bacterial seed-borne ailments, abstract the ability of a plant to create superlative yield or triumph over stress. The advantages of using seeds that are either resistant or tolerant to critical seed-borne diseases or can help preserve substantial agricultural income are plentiful. High-quality tomato seeds are of significant economic importance (Pérez-Pizá *et al*., 2023; Gilardi *et al*., 2024).

3. Fungal Diseases in Tomato Seeds

Since many fungi are common, can cause serious plant diseases, and can spread vertically, there has been a growing interest in the presence of fungi in tomato seeds. Fungi carried by seeds can infect an entire plant, causing significant financial losses and decreasing final product quality. When fungi that spread via seeds are classified as main or secondary fruit illnesses, rejection, and chemical defense increase these losses (Sinno *et al*., 2020; Ma *et al*., 2023).

The strategy of curatively treating plants is insufficient to avoid the success of these pathogens since some of them can cause latent or invisible infections persisting in seeds and infecting asymptomatic plants that generally do not show strong symptoms. A similar situation occurs in the field with infected plants, acting as sources of dissemination and transmission of the pathogen to other plants. Therefore, diseases caused by seed-borne fungi are difficult to manage once established. Certain abiotic and biotic factors influence the onset and progression of various fungal infections in susceptible plants Climate and environmental factors are important abiotic factors that influence the frequency and severity of many fungal diseases. These impacts can be, among other things, limiting, inductive, or resistant. Temporal impacts are particularly significant since a seed-borne pathogen's ability to cause disease may be directly correlated with the season in which it is sown (Goko *et al*., 2021; Dell'Olmo *et al*., 2023).

3.1. Seed-borne Fungal Pathogens

Fungi cause tomato seed decay and seedling wilt worldwide. In the environment, pathogen inoculum is provided through nematodes, soil, and plant debris survival or seed-borne infections beforehand. Once the pathogen colonizes the seeds, it overwinters in the seed coat and embryos. If stored under certain conditions, the pathogen can survive up to 2 years inside the seeds (Hassan, 2020). The most important seed-borne fungal pathogens of tomato are diverse, some of which are described or proposed in seminal or basic references of tomato diseases. This section emphasizes only some seed-borne fungi and illustrates an example from each of them for a better understanding of the role of seed transmission by these pathogens during and after seed production procedures and the possible risks posed by viable infested seeds (Kumar *et al*., 2020). Seeds are the agents of gene transmission for the following crop season. They also link crops of the same or different growth cycles in terms of time, crop type, or place as they are used either as the starting material for sowing or as the final commercial product. They are also involved in marketing and seedling production, which increases the population of seed-borne and soil-borne pathogens in the purchased lots of seeds. Pathogens transmitted by seeds, particularly those causing systemic infection, acquire reproductive and survival advantages over populations transmitted in other ways. In addition, the use of resistant varieties, seed dressings, and the sowing of certified seeds can reduce their incidence (Samreen *et al*., 2021; Wu *et al*., 2022). Some are transmitted from parent to offspring via embryo, and some from seed parts to seedlings by kernels. The most common seed pathogens are fungi, oomycetes, bacteria, and viruses that cause plant disease. These groups are also transmitted to varying degrees by soil and external seed infections entering the endosperm, the cellular space between the outer surface of the embryo and endosperm, or the embryo by remaining dormant inside the seeds. Fungi isolated either inside the seeds or on the surfaces of the seed are classified as internal, external, latent, and endophytic based on their specific positions on the seeds (Fones *et al*., 2020; Pandit *et al*., 2022).

3.2. Symptoms and Effects on Tomato Plants

If infection is established on seeds, the first visible symptoms of tomato plants can be a loss of vigor, a deleterious effect on root growth and top stability, premature wilting, and death of seedlings, which profoundly affect the vitality and field establishment of all commercial plants. In older plants, the most common phenomenon of fungal infection is chlorotic yellowing, browning on the edges and interveinal spaces (necrosis) of cotyledons, primary, and subsequent leaves, and spotting and wilting of stems, flowers, and fruits. In each case, symptoms can range from slight to severe, depending on the time of infection, the virulence of the pathogen, and prevailing environmental conditions. Moreover, symptoms can first appear on one part of a tomato plant and quickly spread to the entire plant, as reflected in variable amounts of dry necrosis linked in part to a massive fungal power of resistance to plant defenses, to the phytosanitary treatment used, and to the hydro mineral status of the plant tissue. If infection takes place after the seedling stage, the vigor and development of tomato plants can be strongly suppressed. In the flowering stage and the ability of plants to bear fruits, tissues around the base of the stem can be abruptly sunken, become brown, and might swell or rot, thus reducing the versatility of fruits and/or the technical characteristics and organoleptic quality requested by the agri-food market. Another learning point is represented by the first signs and spread of the fungus on germinated seeds, which causes serious problems in the substantial loss of two-year-old seeds. An extensive brownish-black seed coat results together with a significant decline in germination percentage (Klimek-Kopyra *et al*., 2020; Abbas *et al*., 2022). Moreover, tomato seeds, which are perceptibly infested, show a high incidence of damping off of seedlings once grown in cubicles. Detecting who, how, and when fungi attack, with environmental, plant vitality, and phonological parameters, is a precise starting advantage for preserving the vitality of lots and effectively controlling seed-borne diseases. The health aspects of seeds are also important to prevent the transmission of diseases to field crops (Hlokwe *et al*., 2020; Walid *et al*.. 2022).

4. Common Fungal Pathogens Affecting Tomato Seeds

A wide variety of fungal pathogens are described, but the common among them are *Fusarium* spp., *Alternaria* spp., *Rhizopus* spp., *Aspergillus* spp., *Penicillium* spp. *Rhizoctonia* spp. Moreover, different species of *Colletotrichum* were also reported causing significant quality and quantity losses in tomato seeds. In the present section, a consolidated picture of such common fungal pathogens of tomato seeds has been presented (Alsudani & Al-Awsi, 2020; Chrapačienė *et al*., 2022; Schmey *et al*., 2023).

4.1. *Fusarium* spp

Fusarium is a cosmopolitan soil-borne fungus that grows as a saprophyte on organic matter or as a parasite of seeds, plants, and other organisms. It is well adapted to a variety of environmental conditions except deserts and ice caps. The genus Fusarium includes many pathogenic species. The tomato seed infected by Fusarium develops symptoms such as rotting and discoloration, postponed germination, and damping off seedlings. It is suggested that seeds of the previous year's crop may carry the fungus because the species of *Fusarium* spp. that cause root rot are encountered in plant debris after harvest (Solankey *et al*., 2021). These species compete with other soil-borne fungi and bacteria during plant colonization. The genus Fusarium contains several species that are the most important fungi that attack tomato crops around the world, and they are of great concern as they inflict economic losses for tomato growers. The disease is most common in southern, hot, and arid regions. Fusarium diseases, moreover, may cause economic losses if losses in crop productivity and quality are not properly managed; at least priming and subsurface irrigation induce better odds of accomplishing acceptable performance for the physiological traits. Some varieties of resistant tomatoes have been mentioned, such as W-1, which encodes a resistance factor from a wild tomato. Moreover, to date, many research opportunities have been devoted to identifying external defenses and other management strategies against these pathogens (Shabeer *et al*., 2021; Gutiérrez-Sánchez *et al*., 2023).

4.2. *Alternaria* spp

Alternaria is another important group of fungi able to infect tomato seeds. Tomato seeds may be contaminated by *Alternaria* spp., which are associated with several diseases; among these, early blight and alternariosis are the most important and may reduce the quantity and quality of production, with a significant economic impact on their market value. Two Alternaria species prevail in the Mediterranean area: *Al. alternata* and *Al. tenuissima* (Giorni *et al*., 2024). They are sub-cosmopolitan phytopathogenic fungi that may affect between 240 and 730 species of crops, agronomically relevant plants, thermophilic fungi, and, more rarely, spruce trees. In some countries, more often than other vegetable crops, the pathogens may affect plants grown for reproduction purposes. This is the case of tomatoes, where the infections may be linked to low germination, with an average value of nearly 4%, almost leading to the elimination of commercialization (Davino *et al*., 2020; Samarah *et al*., 2021).

Both species are in the "speciosae" section. *Alternaria* spp. are the causal agents of both leaf and fruit early blight of tomato, potato, and seed. Once the infection of tomato fruit has started due to favorable environmental conditions, symptoms such as color change or sunken, water-soaked lesions start to develop after 4-5 days of incubation. According to the transmissive capacity of the pathogen by the seed, and therefore the predicted losses at the stand and the market, the control of *Alternaria* spp. in tomato seed becomes critical. Unfortunately, to date, the strategy in use is related to the implementation of good agricultural standards in the tomato production cycle to reduce the possibility of pathogen establishment or proliferation, catching the disease, and probably transmitting it to the offspring. Research and genetic enhancement can provide the market with plant varieties genetically resistant to fungi of *Alternaria* spp. (Hernández-Ochoa *et al*., 2020; Alrudainy & Mshari, 2022).

4.3. *Cladosporium* spp

Tomato seeds have been one of the main sources of primary inoculum of fungi responsible for the emergence of plant diseases. A survey revealed the presence of *Cladosporium* spp. in 45% of the seeds tested. Environmental conditions, such as relative humidity over 92% and temperatures around 24 °C, favor the development of the pathogen. Pathogen progress in the field and on seedlings pot-cultivated in the laboratory was also simulated. On seedlings, leaf spots and general decline were observed. *Cladosporium* spp. The disease cost tomato growers 33% of the yield, with a remark on fruit depreciation and an unfavorable impact on production quality. Sanitary measures have been suggested for faster progress in the reduction of the intensity and dispersion of the disease. Also, some cultural practices can make tomato crops less susceptible to disease, promoting resistance among genotypes and the application of soil that has undergone a mixture for at least 90 days with the inclusion of the biomass (Sinno *et al*., 2020; Metwally *et al*., 2022; Arcidiacono *et al*., 2024).

Some studies on chemical management have been carried out for isolated *Cladosporium* spp. Developing tomato seeds. Even with these progresses, the need to continue certain areas of research with the fungus has been pointed out, as a large group of farmers still apply a mixture of chemicals, and new studies will facilitate fungal control. Contaminated seeds develop as soon as they are collected from the plant, facilitating their identification and assigning them as possible sources of *Cladosporium* spp. Spores can infect the crop, so greater attention has been drawn to the problematic fungal disease in seed banks (Johnston-Monje *et al*., 2021; Rashid *et al*., 2023).

4.4. *Phytophthora* spp

Fungi in the genus Phytophthora can be important tomato pathogens at all crop stages, including the early seedling stage, especially in soils with poor drainage and warm climate conditions. Phytophthora species are well-known fungal-like organisms that belong to the oomycetes. The life cycle of Phytophthora starts with the release of swimmer spores, zoospores, in water-saturated soils. Infection begins when the zoospores encyst on the root surface and develop a germ tube that directly penetrates the roots. Hyphae internally colonize the root and induce the development of broad-spectrum plant immune responses. Upon encountering resistance in the roots, sporangia are produced. The sporangia release new zoospores, which can swim through water to infect nearby seedlings. If there is no water available, sporangia are produced, which can be dispersed by splashing and infecting leaves that have free moisture (Volynchikova & Kim, 2022). The high levels of polygalacturonase produced by the *Phytophthora* spp. Pathogen then aids in expansion through the pectinaceous tissues of roots, stems, and leaves. The motile zoospores of Pythium and Phytophthora are encysted and resist desiccation. Free soil moisture allows the encysted zoospore to 'resuscitate' and release germ tubes. The consequence of this lifecycle development is the irrigation of the nursery area and the germination of *Phytophthora* spp. If the area also has warm temperatures, the disease is rampant and infection leads to root rot and damping-off (Gilbert & Parker, 2023).

Plant root infection initiates with seed germination and growth; therefore, the plant is effectively parasitized immediately. Regardless of where the infection occurs, since the processing tomato is grown for its fruit, the crop must be destroyed to prevent the spread of the disease to the fruit. The symptoms associated with the infections include root and crown rot and damping-off. The root rot symptoms are generally not obvious until the plant has wilted and is pulled away, as affected roots will be blackened, and infections result in the formation of brown, soft rotted areas on the stems, which often exude a pink to red discoloration. Soft, brown lesions on the stems and petioles are also commonly apparent throughout the growing season. Leaf-devastating symptoms of leaf blight are more prevalent in the fruit-bearing plant. The devastating effect of Phytophthora blight on processing tomatoes is implicit because of the value of infested fields, irrigation systems, and seed stock. The disease likes dry heat, of which we typically have an abundance during the growing season, increasing disease pressure. Fresh market field crops are also devastated because infected seed stock affects the transplants (Jones, 2021; Wang *et al*., 2022). Management practices include pesticides and tolerant hybrid tomatoes. Several partially resistant materials are in commercial use, which have greatly reduced the use of toxic pesticides in conventional treatments. Yet, most of the Phytophthora-resistant hybrids for commercial market growers are still Cu-resistant. Few, if any, hybrid tomatoes have PI resistance or polygenic resistance which researchers are still investigating. Phytophthora is one of the major seed pathogen problems in the field and the greenhouse. This pathogen has been blamed for the damping-off of millions of tomato seeds, and as a result, research on developing an economically acceptable and environmentally responsible control for tomato seeds is ongoing. Sporangial counts in water are easily measured and, although colorless, are morphologically different from other tomato pathogens (Scott *et al*., 2020; Giachero *et al*., 2022; Gaikwad *et al*., 2023).

4.5. *Rhizoctonia* spp

Rhizoctonia spp. are cosmopolitan soil-borne fungi that can infect the seeds, seedlings, and adults of many crops, including tomatoes. Symptoms created by Rhizoctonia spp. in tomatoes include damping-off, root rot, and stem rot. As a result of root rot, stunted seedlings have small necrotic spots on the roots and the whole plant will wilt and eventually collapse. Investigations show that *Rhizoctonia* spp. are favored by temperatures ranging between 15°C and 32°C and by a moisture content of 40% to 60%. The current disease severity percentage attributed to *Rhizoctonia* spp., estimated from the total loss caused by the most important fungal pathogens of tomato, ranges from 0% to 2.5% during the seedling stage and 0% to 2% in the adult stage. Management strategies may employ a seed gravity for seed purity selection or treatments to control the pathogen, as well as crop rotation with alfalfa for four years to lower the inoculum density common in the soil. Furthermore, under glasshouse conditions, it is recommended to sow the seeds in a plastic tray 18 days before cold temperature sowing and 25 days before high-temperature sowing (Hlokwe *et al*., 2020; Solankey *et al*., 2021).

The current biological control strategies are limited to wheat and lettuce. *Rhizoctonia* spp. Possess many similarities to other soil-borne pathogens such as *Pythium* spp., *Fusarium* spp., and *Sclerotinia* spp., in that they are soil-borne and their management strategies are based on the environmental conditions and basic understanding of the symptoms and biology of the pathogen. It has been suggested that *Rhizoctonia* spp. has the potential to cause additive interactions with other pathogens and affect tomatoes and potatoes when developing a management program for these more important baseline pathogens in the field. Emerging research reported that mixtures of different genotypes of *F. oxysporum* and *Rhizoctonia solani* within the same crop are more severe. In contrast to *F. oxysporum*, however, there has been no study to show the impact of genetically diverse populations of *Rhizoctonia* spp. on disease expression. This fungus is pathogenic toward tomato seedlings and to examine the cyst population in commercial tomato seeds. If this fungus is found to be pathogenic, it will be recommended that investigations continue to permit a clear understanding of the biology, genetics, and management of *Rhizoctonia* spp. in tomato seeds (Al-Surhanee *et al*., 2021; Mogazy *et al*., 2024).

4.6. Botrytis cinerea

This pathogen is the etiological agent of gray mold and is listed as one of the most important pathogens in tomatoes. The presence of cells of the pathogen in tomato seeds has been reported. The fungus has a necrotrophic lifestyle, moves from senescent tissue to build a necrotic lesion, and enters a phase of constant sporulation. Symptoms of tomatoes caused by this pathogen are necrotic spots on old and mature leaves and softening and water-soaked areas of tomato fruit. The climatic conditions favorable to its growth are high humidity and poor ventilation; in fact, the infection is limited to the part of the fruit directly involved in prolonging the ripening process. The economic damage that the pathogen can cause to tomato crops is due to the reduction of production caused by the susceptibility of the fruit to detachment from the pedicel and rots of varietal fasciation. The pathogen can also cause storage diseases resulting in loss of quality. The control measures for these pathogens are indispensable and integrated to prevent the spread and infection of *B. cinerea* (Peritore-Galve *et al*., 2021; Salem *et al*., 2022).

Furthermore, with one exception, the percentage of the disease was always higher in plants from tomato seeds infected with *B. cinerea* than in those from seeds colonized by *Al. alternata*. The percentage reduction of infected tomato plants derived from seeds infected with either of the two pathogens was almost always less than the others. Furthermore, it was observed that the infected seeds reduced the height of the plant compared to the biomass. Therefore, at the end of the experimentation period, it was found that the adult tomato plants raised from seeds infected with *B. cinerea* had a clear reduction in their biological characteristics and pathogen proliferation (Bika *et al*., 2021; Mahmoud *et al*., 2023).

5. Disease Management Strategies

Management of seed-borne fungal diseases undoubtedly involves the integrated use of some strategies. Laboratory, greenhouse, and field experiments have supplied valuable results. The sanitary measures must begin in the field with cultural practices; however, others can subsequently enhance the reduction of the incidence of fungal diseases. The prospects for the use of antagonists to suppress and control seed-borne fungi and their side effects should be explored more in field experiments. Disease management relies on a combination of (1) cultural practices, (2) seed treatments, (3) the use of biocontrol agents, and (4) the development of resistant plant varieties. In most cases, several strategies may need to be implemented to manage a particular pathogen. Moreover, to assess the overall sustainability of these strategies, an economic dimension should be considered. Disease management strategies differ according to whether the pathogen is seed-borne or not. Economic considerations also underlie disease management practices, since the cost-benefit analysis partially determines how the particular strategies are employed. Despite extensive research in this field, the problem of the resistance of fungal pathogens to fungicides persists. Therefore, it is necessary to conduct further investigations to develop new approaches suitable for seed treatment as well as a multidirectional blended method for disease management (Bisen *et al*., 2020; Rawat *et al*., 2021; Collinge *et al*., 2022).

5.1. Cultural Practices

Fungi are the most devastating pathogens of the three main tomato seed-borne pathogen groups. This necessitates the development and implementation of an array of strategies to protect the tomato and assure the quantity and quality of its seeds. Although several measures are already available, their practical implementation is still inconclusive; hence, the a requirement for careful analysis on the selection of the most efficient strategies. Tomato seed-borne diseases can be effectively managed by minimizing the pathogen and seed reservoirs within and around the tomato fields, preventing or reducing contact between the pathogen, susceptible cultivars, and their alternate hosts, and sowing only "healthy" tomato seeds (Nhi *et al*., 2024).

Cultural practices play a predominant role in managing field and storage diseases of tomato seeds and vegetative organs in conventional, organic, or integrated horticultural systems. They include practices that affect field management, practices that influence natural enemies, and physical, chemical, and biological pre- and post-harvest treatments. Among them, crop rotations and crop spacing are given outstanding importance. Experience has shown that farm field conditions in which crops such as tomatoes provide optimal growth are the same prerequisites by which any deleterious parasite can optimally grow. If pathogen contact is inevitable, the best preventive measure lies in growing a plant that has a high degree of resistance and vigor. The plant, by its resistance, can tolerate the pathogen without any apparent effect on its part. Disease management options must be reliable, acceptable, economically feasible, socially and politically compatible, and environmentally friendly. Also, to be effective, a disease management program must begin with healthy seeds (Panno *et al*., 2021; Fredrick *et al*., 2022). Conditioning cultural practices are only cost-effective and biologically safe. Supporting the farmer community through education and system management is beneficial because farmers also need increased awareness to support a change of mind. The other point is that the implementation of any of these practices is a little challenging in small-scale seasonal crops produced on rural farms by smallholder farmers (Maulu *et al*., 2021).

5.2. Seed Treatments

Chemical seed treatments are most common and effective for controlling infectious pathogens that are transmitted on the seed surface. Seeds are soaked in a diluted chemical treatment solution, and the active chemical may be absorbed into the seed to protect against various pathogen infections. Biological seed treatments primarily help protect the seed from fungal pathogens; there is also some evidence that seed treatments can protect tomato seeds from some bacterial diseases. It is important to realize that proper seed treatment should be selected based on the specific pathogen to maximize the impact of the seed treatment (Lamichhane *et al*., 2020; Shelar *et al*., 2023). There are many different beneficial formulations of biological seed treatments currently available commercially. These types of products are often applied using liquid treatments or using a vacuum air system treatment method. Some positive aspects of seed treatments include improved establishment and development of healthy seedlings, reduced likelihood of seed rotation, and reduced spreading of seed-borne diseases within the entire crop production system, especially when permitted as part of an Integrated Pest Management approach. Although chemical seed treatments are the most effective seed treatments available, some people think the potential yield gain does not always cover the cost of the treatment, especially with decreasing seedling production costs in modern systems. However, alternatives to current seed treatments are being developed, to reduce threats such as resistance, reduce damage to non-target organisms, and eliminate trade or approval requirements (Malik *et al*., 2020; Šerá *et al*., 2021).

5.3. Biocontrol Agents

Some microorganisms, such as bacteria and fungi, act as natural antagonists of pathogens. These biocontrol agents can produce metabolites that reduce the competitiveness and growth of pathogens, defend against pathogens, destroy pathogens, or even directly inhibit pathogen development, which can be a mechanism for the inhibition and control of pathogens. *Trichoderma* spp., *Pseudomonas* spp., *Bacillus* spp., *Streptomyces* spp., and *Chaetomium* spp. can protect seeds from the contamination of soil pathogens (Archana *et al*., 2022). Many studies have been conducted on compounds of fungal origin as commercial bio fungicides to prevent soil-contaminated pathogens in tomato seeds. Nevertheless, very few biocontrol agents are commercially available as seeds. On the other hand, there are many advantages to using biocontrol agents in the soil and on the seed. They are safe for the environment, workers, consumers, ecology, and living resources. In contrast to synthetic fungicides, which are gradually degraded in the environment, biocontrol agents have considerable potential to be developed to protect the seeds of horticultural crops such as tomatoes against fungal pathogens. Lower populations of inoculum and pathogen levels in our field can be achieved by decomposition, stimulated soil, microbiota development, and biological control of pathogens in the soil (Prajapati *et al*., 2020).

5.4. Genetic Resistance

In recent years, the use of resistant varieties as a strategy to manage disease is becoming increasingly relevant. For several plant diseases that are caused by a complex grasp of genes, there is an increasing discovery of the role of resistant genes and QTLs responsible for resistance. LN, Mi, I, I2, and I3 genes are mentioned, among others, as those related to the resistance of *B. cinerea* in world tomatoes. As a result of recent breeding work, resistant tomato varieties with resistance genes and QTLs I2, I2, Mi, and Dd have been prepared. Resistant varieties are also being developed by breeders in Poland; vegetable production is an important branch of agriculture, the greenhouse cultivation of vegetables has been increasing steadily since 2014, reaching 695 ha in 2019 and 2021. Tomato plants are prone to a wide variety of diseases that, if untreated, result in yield losses. Growth in greenhouse crops will only occur if high density and glasshouses are utilized, resulting in favorable conditions for disease development. When discussing healthier tomato cultivation, it is safe to claim that achieving the ideal production conditions involves not just expanding cultivars that are resistant to sickness. There are many cases of related traits but also stimuli or signaling. Additionally, the objective of caring for something that must be removed decisively to guarantee a certain level of crop protection is avoided. Conversely, a cautious approach is necessary when combining resistance with other available control methods in a general management strategy. Nonetheless, it is necessary to research tools such as markers that can be used to recognize new sources of resistance genes in the tomato genome, which is the topic of our research (Panno *et al*., 2021; Ma *et al*., 2023).

6. Future Directions in Research

Ongoing research must be conducted to fill knowledge gaps regarding the fungal pathogens involved in tomato farming operations. Despite some advances in this area, there is a great deal that remains unknown, such as the importance of pathogens occurring at lower concentrations. Furthermore, there is potential to further investigate the influence of abiotic factors, the intermittent nature of symptom expression, the genetic and molecular interactions between pathogens, the introduction of the resistance trait in *Solanum lycopersicum*, the applicability of these research results, and the development of other crop protection strategies such as the use of biostimulants and biofertilizers as management methods to empower plants' defense systems and their ability to interact with other soil microbiota, as well as the development of field resistance tests and the genetic identification of traits for improving tomatoes (Rupasinghe *et al*., 2022; Pham *et al*., 2024).

Nonetheless, a joint effort by researchers and stakeholders in the agricultural sector is required to meet the expectations of the global population while minimizing the environmental impacts of overusing natural resources. Investment in the next generation of high-throughput sequencing technologies and the development of fully sequenced genome-annotated databases of multiple fungal species that cause diseases in tomatoes will make it possible to carry out more profound research into the taxonomy and species structure of the main or more prevalent tropical grocers. In addition to these modern sequencing methodologies, field trial studies and assessment of introduced populations represent the basic steps in the aforementioned (Lebas *et al*., 2022; Nizamani *et al*., 2023).

7. Conclusion

However, a holistic management approach using resistant varieties, seed treatments, fungicides, bio fungicides, and biostimulants integrated dynamically and combined with good agricultural practices offers more efficient, effective, and sustainable solutions. Tomato has great economic and agricultural importance, but there have been few disease surveys conducted to monitor the occurrence of fungi transmitted by seeds. The literature mainly provides studies showing isolated fungi in seeds; this makes it difficult to elucidate the actual impact of pathogens on tomato production. Identifying the diversity of fungi causing seed-borne diseases in tomatoes is essential; they can vary depending on the location, time of harvest, and cultivation practices, and lead to constant risk of fungi occurring in tomato seeds. A serious challenge is to maintain and sustain seed health and subsequent crop performance, which can ultimately lead to environmental, socioeconomic, and human health benefits. Tomato seeds are an essential input for production, so attention should be paid to their health. Studies to better understand and manage seed-borne fungi are essential to prevent future crop losses. Research on the seed microbiome is needed to understand the naturally occurring microbiota, pathogen communities, and antagonistic microorganisms that are involved. A broad vision of emerging problems is essential to develop new management strategies. Tomato is a crop grown across the world and is affected by a wide range of diseases. Fungi are among the most critical biological agents that infect both the vegetative plant parts and fruits leading to massive yield loss and high economic impact on tomato fruit and processing industries. Fungi also transmit their pathogenic biotic components through the seeds and this could be the main source of disease transmission, as well as a survival or primary inoculum for the plants the following season. Unfortunately, our understanding of the major economically important seed-borne fungi in tomatoes is at a low ebb. There is a lack of comprehensive studies to review the concerns and importance of seed health from this valuable vegetable and fruit crop. In such scenarios, a review comes up to provide detailed insights into the important seed-borne fungal diseases in tomatoes.

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