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MANAGING ONION BASAL ROT: BIOLOGICAL PARADIGMS FOR COMBATING FUSARIUM OXYSPORUM F. SP. CEPAE

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ABSTRACT
Onion basal rot caused by Fusarium oxysporum f. sp. Cepae, is a destructive soil-borne disease that significantly constrains onion production worldwide, leading to considerable yield reductions and post-harvest losses. The continued dependence on chemical fungicides for disease control is increasingly challenged by the emergence of fungicide-resistant pathogen populations, environmental concerns and stringent regulatory restrictions. Subsequently, sustainable and environmentally friendly biological paradigms of disease management approaches have gained increasing attention. A comprehensive understanding of the pathogen's etiology, disease cycle, symptomatology and economic impact is essential for developing effective management strategies. Eco-friendly management practices such as biological control agents tri and microbial consortia, botanical extracts and organic amendments have demonstrated considerable potential in reducing disease incidence while minimizing environmental risks. Natural plant defense mechanisms, including structural barriers, phenolic compounds, defense-related enzymes and induced systemic resistance, play a crucial role in suppressing disease development. Recent advances in disease management, including nanobiotechnology, RNA-based biocontrol technologies further enhance the prospects for sustainable disease suppression. Although individual organic approaches may exhibit certain limitations, their integration provides an effective and sustainable alternative to conventional fungicide-based management. Greater emphasis on location-specific integrated strategies and continued research is required to improve the efficacy, adoption, and long-term sustainability of these practices. Such approaches offer promising opportunities for the development of environmentally and economically viable solutions for managing onion basal rot.

KEYWORDS: Fusarium oxysporum f. sp. cepae; Onion basal rot; Organic disease management; Biological control; Induced systemic resistance.

INTRODUCTION
Onion (Allium cepa L.) is one of the world's most extensively grown vegetable crops and is prone to attack by several soil-borne pathogens, including the basal rot pathogen Fusarium oxysporum f. sp. cepae (FOC)[1]. F. oxysporum f. sp. cepae can persist in the soil for a long time in the form of chlamydospores, making it a persistent pathogen. High inoculum levels and suitable environmental conditions can result in significant crop losses or even total crop loss due to basal rot[2]. The biology and epidemiology of F. oxysporum f. sp. cepae have been well researched worldwide, offering valuable insights into the pathogen's infection and survival strategies[3]. Control measures for basal rot are currently based on the use of fungicides, resistant varieties, and biological control agents, and cultural practices (crop rotation, soil solarization and sanitation) to lower soil inoculum levels[4]. Onion is one of the world's most widely consumed vegetable crops and forms the foundation of many culinary traditions 5. Its distinctive taste, processing potential and long storage life make it an important commodity, both fresh and processed [6]. Onion is also an important source of nutritional and medicinal properties[7]. Onion contains bioactive constituents such as flavonoids (such as quercetin), sulfur-containing compounds (e.g. thiosulfinates), phenols, vitamins (particularly vitamin C) and minerals (particularly potassium and calcium)[8]. These are responsible for various biological activities such as antioxidant, antibacterial, anti-inflammatory, and cardiovascular protective effects [9].

Onions are grown in temperate, tropical and subtropical countries throughout the world, with the primary producing countries being India, China, the United States, Egypt and Turkey [10]. India is one of the major producers and exporters, and onion cultivation plays an important role in the socio-economic life of the nation[11]. It is grown in several seasons (kharif, late kharif, and rabi) throughout the year, which ensures its availability throughout the year and supports the livelihoods of millions of small and marginal farmers, and contributes significantly to agricultural GDP and export income[12]. Storable nature, high market demand, and price sensitivities make onions a potential economic and political commodity [13]. Hence, sustainable onion production is necessary for food and economic security [14]. But the persistent nature of basal rot, augmented by environmental factors and constraints of traditional control measures pose a significant threat to sustainable onion production.

Historical Background of Causal Agent of Basal Rot of Onion

The first report of onion basal rot disease was made by Mathur and Sankhala (1963) in Rajasthan, India[15]. Later, Everts et al. (1985) showed that the disease occurs in almost all onion-growing areas of the world[16]. In India, Manimaran et al. (2011) confirmed that basal rot of onion is mainly caused by Fusarium oxysporum [17]. Subsequent studies also demonstrated the involvement of additional Fusarium species, such as F. solani[18] and F. proliferatum[19]. Research from various parts of the world, such as Asia, Europe, America and Africa, has also confirmed the presence of basal rot in Allium species [20-23]. Most recently, Bhat et al. (2023) confirmed the presence of F. acutatum in basal rot disease in India, showing the diversity and dynamics of the pathogen complex [24].

Onion Basal Rot Disease

Onion basal rot is a serious soil-borne fungal pathogen, typically caused by Fusarium oxysporum f. sp. cepae, a form of the fungal species Fusarium oxysporum[25]. Onion basal rot attacks plants at various stages of development, such as seedlings, growing plants and bulbs, and causes decaying and death of tissues and whole plants [26]. The disease generally starts at the root tip or basal plate, with the pathogen entering through and colonizing the vascular tissues, disrupting water and nutrient movement [27]. Symptoms include leaf yellowing and wilting, stunted plants, root death and basal plate rot (Figure 1) [28]. Later in the disease cycle, bulbs show soft watery rot (Figure 2) with white or pink fungal growth [29]. One of the key challenges in controlling this disease is the pathogen's capacity to persist in soil as chlamydospores for several years, allowing it to remain viable in the absence of a host [30]. These resting structures enable the pathogen to survive extreme environmental conditions and are difficult to eradicate [31].

Figure.1 Initiation of rotting of basal plate of onion

Figure.2 Rotten basal plate of onion

The environmental conditions are very important in the development of diseases, and the best conditions are found in soils with temperatures of 25-30°C, deep soil moisture, bad drainage and a persistent mono-cropping system [32]. The infection can take place via infected soil, irrigation water, contaminated planting material, and agricultural tools, which help to spread the infection quickly [33]. Onion basal rot is also a major limitation to sustainable onion production in many countries around the world because of its persistence, adaptability, and general host association [34].

Economic Impact and Need for Sustainable Disease Management

Onion basal rot has a great economic impact at both pre-harvest and post-harvest levels [35]. Averages of 10% to 70% and even 100% under extreme conditions are common losses in terms of yields [36]. The disease decreases the plant stand, the size of the bulb and the general marketable yield and thus decreases farm productivity [37]. Moreover, infected bulbs tend to decay in storage, causing significant losses after harvest, shortened shelf life, and decreased market and export quality [38,39]. The additional spending on the control of disease also contributes to the economic burden [40].

It has a disastrous effect on smallholding farmers, especially in India, where farmers suffer losses in production, which results in an unstable income and fluctuating prices not only to farmers but also to consumers [41–43]. The above challenges underscore the importance of sustainable management approaches.

Traditional methods of control based on the use of chemical fungicides and fumigants are short-term and have several limitations associated with the development of resistance in pathogens and environmental issues [44-46]. Other limitations that have limited their use include soil and water pollution and pesticide residues in foods [47,48]. Organic disease management is a sustainable option that involves the use of biological control agents (Trichoderma, Bacillus, Pseudomonas), botanicals, and organic amendments [49,50]. These methods work via a variety of mechanisms, such as suppression of pathogens, plant defense induction, soil health enhancement, resulting in disease-suppressive soils [51,52]. They also enhance sustainability of the environment and long-term agricultural resilience[53]. Nonetheless, inconsistency in field conditions prompts the need to incorporate holistic organic management approaches in the implementation of uniform and efficient control of onion basal rot [54].

Table.1: Major biological control agents used for management of onion basal rot

Biological control agent	**Target Fusarium species**	**Mode of action**	**Experimental condition**	**Disease reduction/effect**	**Reference**
Trichoderma harzianum	F. oxysporum f. sp. cepae	Mycoparasitism, antibiosis, induced resistance	In vitro, pot, field	Up to 85% reduction in FBR	55
Trichoderma viride	F. oxysporum f. sp. cepae	Competition, enzyme production	In vitro, field	Significant reduction in basal rot	56
Trichoderma asperellum	F. solani	Antibiosis	In vitro	Strong growth inhibition	57
Bacillus subtilis	F. oxysporum f. sp. cepae	Antibiotic production, ISR	In vitro, pot	Effective suppression of FBR	58
Pseudomonas fluorescens	F. oxysporum f. sp. cepae	Siderophore production, ISR	Field	Reduced disease incidence	59
Glomus mosseae (AMF)	F. proliferatum	Improved nutrient uptake, resistance	Pot experiment	Reduced disease severity	60

Etiology and Epidemiology

Fusarium oxysporum f. sp. cepae is the predominant pathogen of onion basal rot, and it can survive and adapt in soil in the long term. The chlamydospores in the soil and plant debris of an infected plant are the main source of inoculum of the pathogen. These dormant spores allow the pathogen to withstand adverse conditions that make it very difficult to control the disease.

Pathogen Biology and Disease Cycle

The pathogenic cycle of the disease starts with germination of chlamydospores under conducive environmental factors. Infection occurs via wounds or natural openings on the onion roots by the pathogen, which then colonizes the root cortex and invades vascular tissues [61]. After being established, the fungus extends vertically to the basal plate and bulb tissues, resulting in gradual rotting. Plants that are infected may have visual symptoms as they grow, or may be symptomless until after harvesting, when the bulb rot will be detected during storage [62]. The secondary spread is by contaminated soil, irrigation water, equipment and infected planting material (bulbs or sets) [63]. Epidemiologically, onion basal rot is mostly monocyclic with soil serving as the inoculum reservoir. Nonetheless, the constant monocropping causes concentration of the populations of pathogens and this causes a more severe disease with time [64]. The survival of the chlamydospores also makes it more difficult to control the disease since the pathogen can stay in the soil even without a host because of the long-term survival in soil[65].

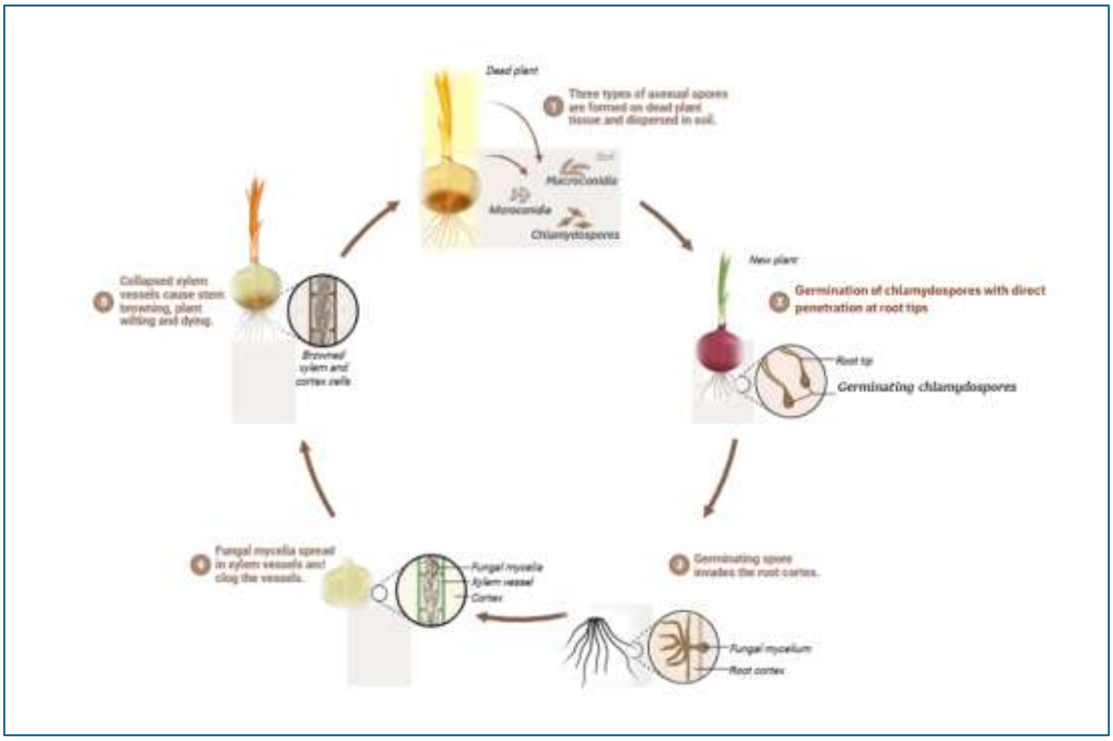

Fig. 5: Life cycle of onion basal rot caused by Fusarium oxysporum f. sp. cepae

Environmental and Ecological Factors Influencing Disease Development

The environment is a key factor in the onset and development of diseases. The soil temperature that is warm (25-30 o C) promotes the growth of fungi and the germination of the spores, thus promoting infection [66]. Poor drainage and high soil moisture provide good conditions in which the pathogen can move and infect the root, promoting disease outbreaks [67].

The severity of disease is also affected by soil characteristics. The soils that are light and sandy with low levels of organic matter tend to be more vulnerable, but soils with high levels of organic amendments and favorable microorganisms may hinder the activities of pathogens [68]. Moreover, other agronomic activities, including constant monocropping, excessive fertilization with nitrogen as well as irrigation mismanagement contribute to aggravating the pressure of the disease by promoting the growth of the pathogen [69].

Host–Pathogen Interactions

Onion plant interaction with Fusarium oxysporum f. sp. cepae is complex and it entails the use of various physiological and biochemical reactions. The pathogen on infection releases cell wall degrading enzymes including cellulases and pectinases, which aid in penetration and colonization of the host tissues [70]. It also generates toxins which disrupt the metabolism of the cells, as well as weaken the plant defense systems. Onion plants in turn respond by employing multiple defense responses such as the build-up of phenolic compounds, cell wall lignification, and pathogenesis-related (PR) proteins [71]. The purpose of these responses is to restrict the spread of pathogens and increase the resistance. The efficacy of these defenses however becomes different in various cultivars with some having partial resistance or tolerance [72]. Recent studies also indicate the importance of the positive rhizosphere microorganisms in promoting plant defense, and preventing pathogen activity by "induced systemic resistance (ISR)" [73].

Symptom Development and Diagnosis

The onion plants that are infected first turn yellow, and then die off, experience dieback of the tip, and stunted growth [74]. Later in the progression of the disease, the leaves fall off and severely afflicted plants can die off earlier than normal resulting in poor field establishment and plant stand [75].

a) Bulb and Root Symptoms

The disease is mainly attacking the basal plate and roots and rotting roots and giving them a brownish colour. Rotting of the base is soft and occurs in the tissue of bulbs and becomes watery and decayed [76]. The advanced stages would manifest themselves in white or pinkish growth of the fungi, or bulbs can shrivel or even rot completely, particularly when foolishly kept [77]. The disease starts with the root infection, progresses to the basal plate colonization and finally to the entire bulb. Early infections can stay in a latent form where the symptoms appear at later stages of growth or after harvest. Severe infections cause destruction of plants and rotting of bulbs [78].

Table 2: Disease progression and associated symptoms

Stage	Symptoms	References
Early Stage	Yellowing of older leaves, slight wilting	[74]
Intermediate Stage	Root rot, stunted growth, leaf dieback	[76]
Advanced Stage	Basal plate decay, bulb soft rot	[78]
Post-Harvest Stage	Bulb shrinkage, fungal growth, storage rot	[62]

b) Conventional and Molecular Diagnostic Techniques

The diagnosis is traditional and is made on the basis of the visual symptoms and fungal isolation and morphological recognition of the pathogen. These techniques are, however, more time-consuming and less specific [45]. Molecular methods, which include PCR-based tests, are accurate, sensitive, and fast in identifying the disease even at the early or latent stage of infection and therefore it is more dependable in confirming the disease [79-83].

Natural Defense Mechanisms in Onion

Onion plants have a built-in structural and biochemical defense mechanisms that limit pathogen invasion and colonization. The first line of defense is the structural barriers like the epidermis, waxy cuticle and thick cell walls which restrict the entry of pathogens [84]. When they are infected, these defenses are strengthened by lignification and suberization, which minimize fungal penetration and distribution [85].

Biochemical Defense Responses (Phenolics, Enzymes)

Onion plants produce antimicrobial compounds in response to infection in the form of phenolic compounds and flavonoids [86]. Enzymes like peroxidase (POD), polyphenol oxidase (PPO) and phenylalanine ammonia-lyase (PAL) involved in defense are also activated and help in strengthening the cell wall and preventing the growth of pathogens [87].

Signalling pathways at the molecular level controlling defense responses involve salicylic acid (SA), jasmonic acid (JA), and ethylene (ET). SA is linked with systemic acquired resistance, whereas JA and ET are mainly involved in the defense against necrotrophic pathogens such as Fusarium, coordination of stress responses and defense gene activation.

Induced Systemic Resistance (ISR) Role

"Induced systemic resistance (ISR)" can be used to improve the capacity of the plant to resist pathogens by stimulating its immune system. This is facilitated by beneficial rhizosphere microorganisms' e.g;[88]. Trichoderma and Bacillus that induce ISR, which results in a faster and more vigorous defense response when attacked by a pathogen, lessening the severity of the disease [89].

Table 3: Natural Defense Mechanisms in Onion

Defense Type	Mechanism	Role in Disease Resistance	References
Physical Barriers	Thick cell walls, waxy cuticle	Prevent pathogen entry	[90]
Structural Changes	Lignification, suberization	Restrict pathogen spread	[91]
Biochemical Responses	Phenolics, flavonoids	Antimicrobial activity	[86]
Defense Enzymes	POD, PPO, PAL	Strengthen cell walls, inhibit pathogen	[87]
ISR	Activation by beneficial microbes	Enhances systemic resistance	[88]

The ability of onion plants to withstand pathogen attack is largely dependent on the activation of structural and biochemical defense mechanisms. Physical barriers, together with induced biochemical responses, play a critical role in restricting pathogen invasion and disease development. These defense strategies enhance the plant's innate immunity and contribute significantly to disease suppression. The information presented in Table 3 highlights the importance of strengthening natural plant defense systems as a sustainable approach to disease management.

Genetic Resistance and Tolerant Varieties

There are onion cultivars and Allium species that are partially resistant to basal rot by improved defense response and less colonization by pathogens [92]. Although full resistance is very uncommon, breeding programs are aimed at the creation of tolerant varieties as long-term viable solution [93].

Table 4: Onion and Allium species showing resistance or tolerance to Fusarium basal rot

Species / cultivar	Resistance level	Growth stage	Remarks	Reference
Allium fistulosum	High	All stages	Non-bulbing species	94
Allium galanthum	Moderate–High	Seedling & bulb	Resistance donor	95
'NuMex Luna'	High	Seedling stage	Short-day cultivar	96
'NMSU 00-13-1'	High	Mature bulb stage	Strong field resistance	97
'Ailsa Craig'	Moderate	Field stage	UK cultivar	98

This table shows inconsistency in onion basal rot resistance between various species and cultivars of Allium. Stringent resistance spreads throughout all the stages of non-bulging species (e.g. Allium fistulosum), whereas some cultivars (e.g. NMSU 00-13-1, NuMex Luna, etc.) have a high resistance at specific stages. These results provide the possibility of resistant genotypes as useful breeding programs and sustainable disease management

Organic Disease Management Strategies

Biological management of onion basal rot is a combination of environmentally friendly practices that inhibit the activity of pathogens as well as increasing the defenses of the plants [99]. Tillage, solarization of soil, irrigation and sanitation of fields decrease the inoculum in the soils and provide hostile conditions to the survival of pathogens. They are supplemented by biological control agents like Trichoderma and Bacillus **(Table 1),** which suppress Fusarium by means of competition, antibiosis, mycoparasitism and systemic resistance induction [100].

Neem and garlic are botanical extracts that have some antifungal effect, interfering with the cell membrane of the fungi and preventing the germination of the spores. The organic amendments also enhance the structure and biodiversity of the soil, which is part of developing disease-suppressive soils. Collectively, these methods will create a multi-layered defense system that means less reliance on chemical fungicides and better disease control and soil health overall [101].

Table 5: Plant extracts and botanical products effective against onion basal rot

Plant source	Plant part / product	Active compounds	Target pathogen	Effect	Reference
Neem (Azadirachta indica)	Oil cake	Azadirachtin	F. oxysporum f. sp. cepae	Strong inhibition of mycelial growth	102
Ethiopian mustard (Brassica carinata)	Seed extract	Glucosinolates	F. oxysporum f. sp. cepae	Significant growth inhibition	103
Rapeseed (Brassica napus)	Seed extract	Isothiocyanates	F. oxysporum f. sp. cepae	Reduced pathogen growth	104
Ashwagandha (Withania somnifera)	Dry leaf biomass	Withanolides	F. oxysporum f. sp. cepae	Reduced FBR incidence	105

Pigweed (Chenopodium album)	Dried biomass	Phenolics	F. oxysporum f. sp. cepae	Suppressed basal rot	[106]

This table shows that the plant-based compounds like azadirachtin, glucosinolates, and phenolics have powerful antifungal effects in preventing the growth of fungi and lowering the occurrence of diseases. These are botanicals which are effective and eco-friendly in the management of onion basal rot.

Synergistic Disease Management Strategies

The effectiveness of organic disease management can be significantly enhanced through the integration of multiple control strategies. Organic amendments improve soil microbial diversity, thereby promoting the activity, establishment, and persistence of biocontrol agents[107]. Simultaneously, botanical extracts suppress pathogen growth and weaken its virulence, making it more susceptible to microbial antagonists. The synergistic interaction between these approaches contributes to enhanced disease suppression and supports sustainable crop protection. This interaction has a synergistic effect, which leads to better disease suppression, better growth of plants, and greater resilience when exposed to field conditions [108]. Integrated organic strategies offer a long-term and more stable control compared to single-method strategies because of their ability to develop a balanced agro-ecosystem and lower risks to the environment [109].

Emerging Technologies

Emerging technologies are providing precise and sustainable solutions for managing onion basal rot. Nanobiotechnology enhances the delivery and efficacy of bioactive compounds through nano-formulations, improving stability, solubility, and targeted action against pathogens such as Fusarium oxysporum [110]. Green-synthesized nanoparticles are gaining attention due to their eco-friendly nature and compatibility with organic systems [111]. Nano-encapsulation of plant extracts and biocontrol agents increases antifungal efficiency and prolongs activity, thereby reducing application frequency and environmental impact [112,113].

RNA-based Biocontrol Approaches

RNA-based technologies especially “RNA interference (RNAi)” is a new technology that is highly specific and specific in the management of diseases. This is a technique that entails the silencing of crucial genes of the pathogen, which in turn provokes its growth and pathogenicity [114]. “Spray-induced gene silencing (SIGS)” enables the extracurricular use of the “double strand RNA (dsRNA)” targeting techniques to ferment fungal pathogens without modifying the plant genome [115]. These strategies are species-specific, environmentally safe, and minimize off-target effects, so it is very appropriate when it comes to the combination into sustainable and organic plant protection strategies [116].

Consortia and Formulations of Microbes

Microbial consortia, which includes useful microorganisms, including Trichoderma, Bacillus, and mycorrhizal fungi are becoming increasingly relevant in sustainable agriculture [117]. These microbes synergistically inhibit pathogens, improve nutrient absorption and activate plant defense mechanisms [118]. High-level formulations enhance their shelf life, stability, and performance in the field. These types of consortia also help in developing disease-repressive soils, which is a long term and holistic approach of controlling onion basal rot and enhancing crop productivity [119].

Table 6: Advances in Sustainable Plant Protection

Approach	Description	Advantages	References
Nanobiotechnology	Nano-formulations of bioagents	Targeted, efficient delivery	[120]
RNA-based Control	Gene silencing (RNAi, SIGS)	High specificity, eco-friendly	[121]
Microbial Consortia	Mixed beneficial microbes	Improved soil health and resistance	[122]

The emerging technologies have the potential of improving efficiency, precision, and sustainability in the management of the disease. These inventions are a new step in the ecologically friendly approaches to plant protection (Table 6).

Limitations

Although there has been advancement in the organic control of onion basal rot, there are several constraints that limit its application at a field-scale. Organic strategies have a fluctuating performance because they are subject to environmental influences like the type of soil, climate and the variety of micro-organisms. Biological control agents tend to perform optimally when used in controlled environments but give inconsistent outcomes in various agro ecosystems.

Organic inputs are also slower acting than chemical fungicides and thus can only be effective in severe disease situations. Moreover, there are problems with standardization, stability of formulation and shelf-life of bioagents and botanicals which hamper large scale implementation. Long term management is further limited by the lack of resistant cultivars.

Other factors influencing adoption include economic limitations, low awareness of the farmers and lack of extension. Furthermore, there is a shortage of large-scale and region-specific field validation studies that could be used to come up with reliable and generalizable recommendations.

The use of fungicides has resulted in the emergence of fungicide-resistant strains of Fusarium oxysporum f. sp. cepae due to the repeated and indiscriminate use of chemical fungicides. Repeated consumption of the same active ingredients diminishes their efficacy as time goes on and higher doses are required or other chemicals, further raising the cost of production and environmental hazards. Fungicides may cause soil health to be compromised, perturb beneficial microbes, and pollute soil and water systems. The accumulation of residues poses a challenge to the safety of food and environmental sustainability. The presence of strict rules on maximum residue limits (MRLs), the growing demand of produce that is residue-free can result in rejection in export markets and decrease in consumer acceptance.

Future Perspectives

Further studies on onion basal rot should be on integrated and mechanism-based control methods that integrate cultural, biological and botanical control methods with enhanced field uniformity. Molecular breeding and genomics have provided a great opportunity to make resistant or tolerant onion cultivars by identifying resistance genes, quantitative trait loci, and relevant defense pathways salicylic acid (SA), jasmonic acid (JA) and ethylene (ET). Enhancement of these genetic and molecular strategies can contribute to the development of sustainable resistance to Fusarium oxysporum f. sp. cepae and lessen reliance on external input.

Concurrently, precision agriculture and research on microbiomes are becoming an important instrument to sustainable disease management. Awareness of plant-microbe interaction and the establishment of successful microbial consortia can enhance disease-resistant soils and enhance greater plant immunity, in the field conditions. Precision technologies, such as sensor-based monitoring and target bio input application can maximize disease control with less cost and environmental impact. In addition, field validation, research with farmers, and facilitating policy frameworks are also critical to facilitate adoption and scalability of these solutions, which eventually will create sustainable and economically viable management of onion basal rot.

CONCLUSION

Onion basal rot management should be a holistic integrated strategy because using individual control measures is not sufficient in the management process because of the persistence of the pathogen and environmental fluctuations. Plant defense systems and organic management strategies such as cultural controls, biological control agents, botanical extracts, and organic amendments can be integrated to form a multi-layered approach to sustainable disease suppression and improve the health of soil and plants. Incorporation of molecular understanding, especially defense signalling pathways, including SA, JA, and ET, and microbiome-based interventions enhance plant resistance and enhance the uniformity of control strategies. Besides this, new technologies like precision agriculture and enhanced bioformulations can streamline the timing, application, and efficacy of such interventions. Nevertheless, effective implementation is conditional upon the pressure of overcoming the issues of field variability, formulation stability, and mass application. Consequently, scientific progress, coupled with the awareness of farmers, area-based approaches, and enabling policy frameworks will be needed to make onion basal rot economically viable, sustainable, and long-terms.

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