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MANAGEMENT OF ROOT ROT AND DAMPING-OFF DISEASE IN PAPAYA (*CARICA PAPAYA*) OVER THE YEARS: A REVIEW

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ABSTRACT

Papaya (*Carica papaya* L.) is a significant tropical fruit crop valued for its nutritional and economic contributions. However, root rot and damping-off diseases, primarily caused by *Phytophthora*, *Pythium*, *Rhizoctonia solani*, and *Fusarium* species, pose major threats to papaya cultivation, particularly in regions like Bihar, India. Historically, disease management has evolved from basic cultural practices and sanitation to chemical control, and later to integrated approaches incorporating biological control and resistant cultivars. Recent advancements have introduced molecular diagnostics, marker-assisted breeding, CRISPR-Cas9 genome editing, precision agriculture, nanotechnology-based fungicides, and microbial consortia applications. These innovations have significantly enhanced disease detection, resistance breeding, and targeted management while promoting sustainability. Modern strategies emphasize integrated disease management, reducing chemical inputs, and fostering environmentally responsible practices. Future prospects involve developing multi-pathogen resistant cultivars, understanding pathogen evolution, and improving the integration of advanced technologies into sustainable farming systems to ensure resilient and productive papaya cultivation.
***Keywords*:** Damping-off, Integrated disease management, Papaya disease management, Root rot.

Introduction

Papaya (*Carica papaya* L.) is a vital tropical fruit crop recognized globally for its nutritional and economic importance. Originating from Central America, papaya has become extensively cultivated throughout tropical and subtropical regions due to its rapid growth, short gestation period, and high economic returns (Chan & Baharuddin, 2012). India ranks among the top global producers of papaya, contributing significantly to the world's papaya supply. The favorable climatic conditions, coupled with fertile soils, have facilitated widespread papaya cultivation across several Indian states, notably Andhra Pradesh, Gujarat, Karnataka, Maharashtra, West Bengal, and Bihar (FAO, 2021).

Bihar, situated in the eastern part of India, has seen a marked increase in papaya cultivation, driven by growing domestic and international demand. The agro-climatic conditions in Bihar, characterized by hot, humid summers and relatively mild winters, provide a conducive environment for papaya cultivation, enabling farmers to achieve high productivity and profitability. Additionally, papaya farming has emerged as a crucial component of Bihar's agricultural economy, providing livelihoods to thousands of farmers and significantly contributing to rural development.

However, the expansion of papaya cultivation has not been without challenges. Root rot and damping-off diseases have emerged as significant constraints, threatening papaya productivity and sustainability. These diseases are primarily caused by soil-borne pathogens such as *Phytophthora* spp., *Pythium* spp., *Rhizoctonia solani* and *Fusarium* spp., which thrive under the warm, humid conditions prevalent in Bihar and other papaya-producing regions of India (Bora & Bora, 2020). Among these pathogens, Phytophthora and Pythium species have been particularly destructive, causing severe seedling mortality, plant wilting, stunting, and eventual death, thereby leading to significant economic losses.

In Bihar, the incidence of root rot and damping-off diseases has escalated due to several factors, including intensive cultivation practices, poor soil drainage, continuous cropping systems, and inadequate disease management practices. Studies have indicated that the losses incurred due to these diseases can range from 20% to over 60% under severe outbreak conditions (Singh *et al.*, 2008). This scenario underscores the critical need for effective and sustainable disease management strategies to safeguard papaya production and enhance the economic well-being of farmers.

Over the years, various approaches have been adopted to combat root rot and damping-off diseases. These include cultural practices such as crop rotation, improved soil drainage, and the use of resistant or tolerant cultivars. Chemical methods involving fungicides and biological control measures employing antagonistic microorganisms have also been widely utilized. However, the indiscriminate use of chemical fungicides has raised environmental concerns and the potential risk of developing pathogen resistance, prompting a shift toward integrated disease management (IDM) strategies (Ventura *et al.*, 2004).

Integrated disease management strategies that combine cultural, biological, chemical, and resistant cultivar approaches have shown promise in reducing disease incidence and improving papaya yield. In India, particularly in Bihar, research and extension efforts have intensified to promote IDM practices, emphasizing sustainable agriculture and environmental conservation. These efforts have involved the identification and dissemination of region-specific disease management practices tailored to local conditions and resource availability (Mitra, 2005). Effective management strategies have evolved significantly over the years.

Management Strategies in the Early 20th Century (1900-1950)

Early in the 20th century (1900-1950), the management of root rot and damping-off diseases in papaya primarily relied on cultural practices aimed at reducing pathogen inoculum levels in agricultural fields. At this time, the scientific understanding of the biology and epidemiology of soil-borne pathogens was rudimentary, limiting the effectiveness of control measures (Walker, 1952). Crop rotation was among the most common strategies employed, where farmers rotated papaya cultivation with other crops less susceptible to soil-borne pathogens. The primary goal of crop rotation was to disrupt the pathogen lifecycle by depriving them of their host plants, thereby reducing their inoculum load in the soil (Agrios, 2005).

Sanitation was another critical cultural practice extensively implemented during this period. Farmers regularly practiced the manual removal and destruction of infected plants and plant debris, often through burning or deep burial, to minimize the risk of pathogen persistence and spread (Stevens, 1939). Additionally, growers emphasized the importance of maintaining clean cultivation practices, ensuring that seeds and planting materials were free from contamination, thus attempting to prevent disease introduction and establishment in new fields (Whetzel, 1929).

Despite these efforts, the effectiveness of these traditional cultural practices was often inconsistent and limited. The fundamental constraints included the lack of detailed knowledge regarding pathogen survival, reproduction, and modes of dissemination, leading to incomplete pathogen eradication and frequent disease resurgence (Walker, 1952; Agrios, 2005). Consequently, substantial economic losses persisted, driving the necessity for more scientifically grounded approaches in subsequent decades.

Chemical Control Era: Mid 20th Century (1951-1980)

The mid-20th century (1951-1980) marked a significant transition in the management of root rot and damping-off diseases in papaya cultivation, as chemical control methods gained dominance. During this period, substantial advancements in agricultural chemistry led to the widespread adoption of fungicides, which significantly reduced disease incidence and severity compared to traditional cultural methods (Agrios, 2005). The advent and popularization of fungicides such as metalaxyl, copper oxychloride, and captan transformed plant disease management practices and markedly improved crop productivity.

Metalaxyl, a systemic fungicide introduced in the 1970s, became particularly favored due to its effectiveness against oomycete pathogens like Phytophthora spp. and Pythium spp., which are responsible for severe root rot and damping-off diseases in papaya. The systemic nature of metalaxyl enabled it to be absorbed by plant tissues, providing both preventive and curative action and offering robust protection against these pathogens (Gisi & Sierotzki, 2015).

Copper-based fungicides, especially copper oxychloride, were extensively employed for their broad-spectrum antimicrobial properties. Copper compounds had been used earlier, but their use significantly expanded during this era due to their affordability, efficacy, and broad-spectrum activity. Copper oxychloride provided effective disease suppression by forming protective barriers on plant surfaces, thereby preventing pathogen penetration and colonization (Oliver & Hewitt, 2014).

Captan, a non-systemic protective fungicide introduced earlier but gaining considerable prominence during this period, was widely utilized due to its effectiveness in preventing fungal infections at the seedling stage, a critical phase susceptible to damping-off diseases. Captan provided a robust protective layer, significantly enhancing seedling survival and overall plant vigor (Yang *et al*., 2011).

However, the widespread and frequent application of these chemical fungicides soon led to various challenges. Issues such as the development of pathogen resistance became evident, as continuous fungicide exposure selected resistant pathogen strains, reducing the effectiveness of these chemicals over time. Furthermore, environmental concerns emerged due to the extensive use of chemical fungicides, particularly regarding soil health, biodiversity, and the potential contamination of water resources (Oliver & Hewitt, 2010).

Another critical issue was the detection of chemical residues in harvested fruits, raising concerns about consumer safety and compliance with international trade standards. These residues affected the marketability and export potential of papaya, prompting increased scrutiny and stricter regulations regarding chemical use in agriculture (Campbell, 1989).

Consequently, these emerging challenges highlighted the necessity for developing more sustainable disease management approaches, leading to the exploration of integrated disease management practices that combined chemical control methods with cultural, biological, and resistant cultivar strategies.

Emergence of Integrated Pest Management: Late 20th Century (1981-2000)

During the late 20th century (1981-2000), the concept of Integrated Pest Management (IPM) emerged prominently as a balanced, sustainable approach to managing root rot and damping-off diseases in papaya cultivation. IPM emphasized integrating various control strategies, including biological, cultural, chemical, and host-plant resistance methods, aimed at minimizing chemical inputs and environmental impacts while ensuring effective disease management (Cook & Baker, 1983).

A significant development during this period was the introduction and popularization of biological control agents as viable alternatives to chemical fungicides. Among the most studied and adopted biocontrol agents were Trichoderma spp., Bacillus subtilis, and Pseudomonas fluorescens. These microorganisms exhibited strong antagonistic activities against a range of soil-borne pathogens responsible for papaya diseases. Trichoderma species gained particular attention due to their multifaceted mechanisms, including competition for nutrients and space, mycoparasitism, and the induction of plant resistance responses (Harman *et al*., 2004).

Bacillus subtilis, a beneficial soil bacterium, emerged as another critical biocontrol agent because of its ability to produce antifungal compounds, stimulate plant growth, and enhance systemic resistance in plants. Its application demonstrated effective suppression of soil-borne pathogens, promoting healthier papaya seedlings and plants (Kloepper *et al*., 2004). Similarly, Pseudomonas fluorescens was widely recognized for its antagonistic activity, primarily attributed to the production of secondary metabolites, including antibiotics and siderophores, which significantly reduced pathogen populations in the soil (Weller, 1988).

Research during this period also highlighted the beneficial role of organic amendments in disease management. Amendments such as compost and neem cake became essential components of IPM strategies, significantly enhancing soil health and suppressing pathogen populations. Compost application improved soil structure, increased microbial diversity, and promoted beneficial microbial populations capable of suppressing disease-causing pathogens through competition, antagonism, and induction of systemic resistance in plants (Hoitink & Boehm, 1999).

Neem cake, a byproduct of neem seed processing, was particularly effective due to its inherent antifungal and insecticidal properties. Studies demonstrated that neem cake amendments substantially reduced pathogen populations and improved papaya plant vigor, consequently reducing reliance on chemical fungicides (Dohroo & Gupta, 1995).

Control

Seed treatment with 0.1% solution of Carbendazim-50% wp for eight hours and basal drenching by Mancozeb (64%) + Metalaxyl (8%) @ 0.25% along with two times additional soil drenching with Mancozeb (64%) + Metalaxyl (8%) @ 0.25% solution

Seed treatment with Carbendazim 50% wp @ 0.1% solution for eight hours + basal soil drenching with *Trichoderma viride* @ 1% followed by two additional soil drenching with Copper oxychloride @ 0.3% at the interval of 20 days

Fig. 1 : Comparative efficacy of chemical, and integrated treatments over control in managing root rot and damping-off in Papaya (courtesy Dr. R. N. Singh)

A study made by Singh *et al.* 2019, on comparative efficacy of chemical, and integrated treatments over control in managing root rot and damping-off in Papaya observed that seed treatment with 0.1% solution of Carbendazim-50% wp for eight hours and basal drenching by Mancozeb (64%) + Metalaxyl (8%) @ 0.25% along with two times additional soil drenching with Mancozeb (64%) + Metalaxyl (8%) @ 0.25% solution was at par with seed treatment with Carbendazim 50% wp @ 0.1% solution for eight hours + basal soil drenching with Trichoderma viride @ 1% followed by two additional soil drenching with Copper oxychloride @ 0.3% at the interval of 20 days (Fig. 1)

The late 20th century witnessed a notable shift towards more sustainable, environmentally friendly approaches in papaya disease management. Integrated Pest Management practices that combined biological agents, organic amendments, cultural practices, and minimal chemical interventions provided farmers with more effective and environmentally responsible methods for managing root rot and damping-off diseases.

Molecular and Biotechnological Advancements: Early 21st Century (2001-2015)

The early 21st century (2001-2015) saw significant advancements in papaya disease management, primarily driven by rapid developments in molecular biology and biotechnology. Advanced molecular techniques, including polymerase chain reaction (PCR), DNA sequencing, and molecular markers, became essential tools for accurate pathogen identification and characterization. These advancements provided deeper insights into pathogen diversity, population structure, and epidemiology, significantly improving our understanding of plant-pathogen interactions (Cooke & Duncan, 1997; Lievens *et al*., 2005).

Utilization of molecular diagnostics enabled precise detection and differentiation of pathogens at early infection stages, facilitating timely intervention and targeted management practices. These technologies greatly improved the effectiveness and specificity of disease management strategies by accurately identifying pathogen strains and their virulence factors (Miller *et al*., 2009).

Breeding programs became increasingly important, with significant efforts directed towards developing resistant or tolerant papaya cultivars. Incorporation of genetic resistance became a priority in these breeding strategies, aiming to develop cultivars capable of resisting or mitigating the impact of soil-borne pathogens, particularly *Phytophthora* spp. and *Fusarium* spp. Advances in genomic selection and marker-assisted breeding accelerated the identification and incorporation of resistance traits into papaya breeding lines, making the process more efficient and targeted (Luby & Shaw, 2001).

During this period, there was also a significant emphasis on integrated management practices combining genetic resistance with biocontrol agents and judicious chemical fungicide applications. Biocontrol agents, such as Trichoderma spp., Bacillus subtilis, and Pseudomonas fluorescens, continued to be important components of integrated disease management, often employed synergistically with resistant cultivars to provide enhanced protection (Harman *et al.*, 2004; Ongena & Jacques, 2008).

The early 21st century also marked an increased focus on sustainable agricultural practices. Efforts were concentrated on reducing chemical inputs and minimizing environmental impact by optimizing fungicide usage through precision agriculture techniques. Strategies such as targeted fungicide applications, improved cultural practices, and enhanced monitoring through predictive models helped reduce chemical reliance, thus promoting sustainability in papaya cultivation (Gilligan, 2008).

This period was characterized by an integrated and holistic approach to managing root rot and damping-off diseases in papaya, emphasizing sustainability, environmental stewardship, and enhanced productivity.

Recent Innovations in Disease Managemnt (2016-Present)

Recent advances (2016-present) in managing root rot and damping-off diseases in papaya cultivation have been characterized by the integration of precision agriculture, biotechnology, and innovative bio-control methods. These contemporary practices are aimed at enhancing disease resistance, sustainability, and productivity, while simultaneously minimizing environmental impacts.

Biotechnological interventions, particularly molecular breeding and genome editing techniques such as CRISPR-Cas9, have emerged as powerful tools in developing papaya cultivars with enhanced pathogen resistance. Molecular breeding strategies, employing genomic selection and marker-assisted selection, have significantly accelerated the identification and incorporation of resistance genes against major pathogens, including Phytophthora spp. and Fusarium spp. (Kole *et al.*, 2016). CRISPR-based genome editing has revolutionized plant breeding by precisely introducing desirable traits and significantly reducing breeding timelines. Recent research has demonstrated promising results in using CRISPR-Cas9 technology to introduce resistance against soil-borne pathogens in papaya, thereby substantially improving disease management efficacy (Chen *et al.*, 2019; Zaidi *et al.*, 2019).

Advancements in precision agriculture have enabled precise monitoring and targeted management of diseases, enhancing efficiency and sustainability. Techniques such as remote sensing, geographic information systems (GIS), and drone-based applications facilitate early detection of disease hotspots, enabling timely and targeted interventions. These precision agriculture tools significantly reduce chemical fungicide use by accurately applying treatments only to affected or high-risk areas, thereby reducing environmental contamination and optimizing resource use (Mulla, 2013).

Nanotechnology-based fungicides represent another significant development, offering targeted pathogen control with substantially reduced environmental impacts. Nanoparticles, such as silver, zinc oxide, and copper oxide, exhibit potent antimicrobial properties and improved bioavailability, enhancing their efficacy against plant pathogens even at lower application rates. Research has indicated that nanofungicides effectively suppress disease pathogens while minimizing residues in harvested fruits and soils, thereby supporting sustainable papaya cultivation (Servin & White, 2016; Kah & Hofmann, 2014).

Additionally, microbial consortium applications and bio-priming of seeds have gained prominence as effective strategies for disease management. Bio-priming involves pre-treatment of seeds with beneficial microorganisms, such as Trichoderma spp., Bacillus subtilis, and Pseudomonas fluorescens, enhancing seed germination, seedling vigor, and resistance against soil-borne pathogens. Microbial consortia, comprising multiple beneficial microorganisms, offer broader-spectrum pathogen suppression and improved plant growth promotion, significantly reducing damping-off incidence in papaya seedlings (Singh *et al.*, 2015; Deshmukh *et al.*, 2020).

The recent advances have significantly enhanced papaya disease management practices through biotechnological innovations, precision agriculture, nanotechnology, and advanced biological methods, reinforcing the move towards sustainable and effective disease management strategies.

Conclusion and Future Prospects

Management strategies for root rot and damping-off diseases of papaya have significantly evolved over the decades, progressing from basic cultural practices to advanced biotechnological and precision agricultural approaches. Current management integrates genetic resistance, biotechnology-driven solutions, precision agriculture, and biological control strategies, focusing increasingly on sustainable practices to minimize environmental impact. Genetic resistance, enhanced through molecular breeding and genome editing techniques such as CRISPR-Cas9, offers durable solutions by developing resilient cultivars capable of withstanding pathogen attacks. Precision agriculture facilitates targeted disease management, optimizing the use of resources and significantly reducing chemical inputs. Additionally, biological control agents, microbial consortia, bio-priming, and nanotechnology-based fungicides have demonstrated efficacy in improving seedling vigor and reducing disease incidence.

Looking ahead, continued research should focus on understanding pathogen evolution, developing multi-pathogen resistant cultivars, and improving the integration of innovative technologies within sustainable agriculture systems. Enhanced collaboration between researchers, extension services, and farmers will be crucial in translating scientific advances into practical applications, ensuring healthier and more productive papaya cultivation globally.

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