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Integrated Insights into Papaya Damping off Infection Caused by *Fusarium oxysporum*: Prevalence and *InVitro* Management Strategies in Sindh Province

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ABSTRACT

Papaya (*Carica papaya* L.) is an economically important fruit crop cultivated widely in tropical and subtropical regions. In Sindh Province, Pakistan, papaya production is increasingly constrained by damping-off disease, primarily caused by *Fusarium oxysporum*. The pathogen infects germinating seeds and seedlings, leading to poor germination. Its ability to survive in soil and crop residues as chlamydospores makes its control difficult. This review highlights the prevalence of damping-off in papaya nurseries of Sindh Province and evaluates *invitro* management strategies. Fungicides such as Carbendazim, Difenconazole, and Nativo have been reported to significantly inhibit *F. oxysporum*, but long-term use raises concerns about fungicide resistance, environmental hazards, and input costs. Alternatively, botanical extracts (e.g. neem, eucalyptus, clove etc.) and biocontrol agents including *Trichoderma harzianum*, *Bacillus subtilis*, and *Pseudomonas fluorescens* have shown promising antifungal activity, offering safer and sustainable management options. An integrated approach combining cultural practices, judicious fungicide use, botanical extracts, and biological control is recommended for effective management of damping-off in papaya nurseries. Strengthening research on pathogen variability, infectious disease epidemiology, and large-scale validation of eco-friendly treatments under Sindh's agro-ecological conditions will be vital for reducing losses and sustaining papaya production.

Keywords: *papaya*, damping-off, *Fusarium oxysporum*, fungicides, botanicals, biocontrol, integrated disease management.

INTRODUCTION

Papaya (*Carica papaya* L.) is a nutritionally and economically valuable fruit crop cultivated widely in tropical and subtropical regions. It is rich in vitamins, antioxidants, and enzymes and is increasingly cultivated in Pakistan due to its high demand and nutritional importance (Ali et al., 2022). In Sindh Province, papaya contributes significantly to farmer income and local markets; however, its production is threatened by soil-borne diseases, particularly damping-off.

Damping-off is a destructive disease affecting papaya seedlings at the nursery stage. It is caused mainly by soil-borne fungi such as *F. oxysporum* and *Pythium* spp., which attack young seedlings, resulting in poor germination, seedling collapse, and significant stand loss (Khan et al., 2020a). The pathogen *F. oxysporum* is notorious for its long survival in soil as chlamydospores and plant debris, making management extremely difficult (Sharma & Gupta, 2019). Disease severity is aggravated under favorable

conditions such as high soil moisture, continuous cropping, and poor nursery hygiene (Patel et al., 2018).

In Sindh and other papaya-growing regions of South Asia, *F. oxysporum* is considered an emerging threat. Studies on related crops have shown high disease incidence in nurseries;

Conventional management relies heavily on chemical fungicides such as Carbendazim, Difenconazole, and Nativo, which have demonstrated significant inhibition of *F. oxysporum* in vitro (Kumar et al., 2021; Memon et al., 2016). However, their long-term use raises concerns about fungicide resistance, high costs, and environmental hazards (Singh et al., 2017). As alternatives, plant-based extracts (e.g. neem and eucalyptus) have shown strong antifungal activity against *Fusarium* spp. (Naz et al., 2019), while biocontrol agents such as *T. harzianum*, *subtilis*, and *Pseudomonas fluorescens* have been widely reported to suppress pathogen growth and promote seedling vigor (Iqbal et al., 2021; Hussain et al., 2023).

Therefore, understanding the prevalence of papaya damping-off caused by *F. oxysporum* in Sindh and exploring effective in-vitro management strategies is essential. This review focuses on disease occurrence in Sindh Province and evaluates chemical, botanical, and biological control approaches to provide a sustainable basis for disease management in papaya nurseries.

Importance of papaya: Papaya is a fruit native to tropical and subtropical areas of the world. "It belongs to the Caricaceae family and is widely used in traditional medicine for disease management." It is widely used to cure a variety of diseases in folk medicine using various parts of *C. Papaya* (Zakaria, L. (2023). Besides vitamins A, E, and C, which are antioxidants and minerals like In addition to the minerals magnesium and potassium, the B vitamins folic acid and pantothenic acid, and fiber, it also contains vitamins A, B1, and B2. As well as fiber. (Alfred et al., 2022). Ultimately, papaya's antioxidant activity plays a role in preventing pathogenesis by counteracting free radical generation. A valuable component that contributes to lower cholesterol, on the other hand, is fiber. Papain, chymopapain, glycyloendopeptidase, and caricain are all cysteine proteinases found in Papaya latex. The fruit, leaves and roots all have different proteinase concentrations (MATONDO et al., 2008). Overall, papaya and its contents are a miracle in the diagnosis, treatment, and prevention of a variety of illnesses, including cancer and cardiovascular disease. Human skin Detroit 550 fibroblasts under oxidative stress caused by H_2O_2 . Were exposed to papaya seed, water extract, which exhibited significant antioxidant properties *C. papaya* seeds and methanolic extracts demonstrated anti-inflammatory efficacy however the findings were lower than those of common anti-inflammatory medications such as aspirin, which had an 85.7 percent inhibition. In vitro investigations are summarised in this review. Poultry feeds have been supplemented with seed because of its high levels of crude protein, fat and ash content (Adesuyi et al., 2011). Growth promoters, anti-microbial and anti-parasite factors as well as immunomodulatory agents and anti-inflammatory agents are among the functional qualities of papaya seed Kadiri et al. (2016), Muazu et al. (2020) and Kumar et al. (2017). Because it is nutritious and produces at a reasonable cost, the papaya seed may be utilized in poultry diets to enhance the health and well-being of the birds. Throughout the year, Papaya is a tropical fruit that may be found (Ameen et al., 2012). Fruits like papaya are frequently served fresh, either as a dessert or in juice form. In the flesh of the papaya, there are black seeds. The papaya seed, which makes up roughly 16% of the fresh fruit weight, is regarded as a waste product (Comerford et al., 2023).

Papaya's nutritional value: Papaya is high in natural vitamins and minerals and low in calories. It is the fruit of choice for obese people trying to reduce

weight due to the comparatively low calorie content (32 cal/100 g of ripe fruit). Compared to other fruits like apples, guava, sitafar, and plantain, papaya has very little carotene, which helps minimize free radical damage. Tolerated sufferers who are unable to digest the wheat protein gliadin, papaya has the ability to tenderize meat if treated with crude papain. This information is being used to cook beef with raw papaya to soften and make it more palatable. Outlined the 100 g of fruit's nutritional content. 100 g of Linn's nutritional value. Increase appetite, lessen menstrual discomfort, tenderise meat, and soothe nausea as an anti-acne therapy (Arvind et al., 2013). 5.2 Fruit A range of vital nutrients, such as provitamin A, carotenoids, vitamin C, vitamin B, lycopene, dietary minerals, and dietary fiber are all abundant in papaya fruit, which is also a great source of them. Danielone is one of the phytoalexins that could be found in papaya fruit.

Production of papaya in Pakistan: Industry estimates indicate that the commercial cultivation of papaya fruit is profitable. An input output economic study (1:1.7) on papaya growers in Karachi, Pakistan, found that they made an average gross profit of PKR 0.55 million from their plants (Wang, et al., 2025).2.4. Area and production of papaya in Sindh

In Sindh papaya cultivated in coastal regions of roughly 1600 acres under cultivation with yearly yield of 8000 tonns. Papaya cultivated in Sindh's Thatta and Malir districts is recognized for its flavor and size. Papaya seed is sown during the month of March to raise nursery and transplanting is conducted during the month of April (Comerford et al., 2023).

Losses due to disorders at glob level of papaya: Their total expenditure, however, was PKR 0.20 million yes-1. Thus, farmers on average suffer considerable losses in the form of revenue loss and in the case of costly fruits to consumers. For example, this disaster resulted in the loss of USD 29 million in Brazil (Wang, et al., 2025). The loss is equivalent to USD 820 ha⁻¹. In India, this insect attacked more than 60 crops, including papaya, between 2008 and 2010 and destroyed 10-60 percent of the crop. Papaya production in Mexico is also the major cause of papaya mealybug attacks, which states that papaya mealybugs in Pakistan are considered to be one of the most serious technical difficulties in continuing papaya production in the region (Bajwa et al., 2018).

Global production of papaya: Data from the Food and Agriculture Organization (FAOST, 2018) illustrates the Global production of papaya 13.2 million (M) metric tons (t) of papaya were produced in 2016. In value terms, the 2021 papaya production is estimated to reach X USD at export prices. Gross output is expected to expand by +X% annually between 2012 and 2021, while trend patterns indicate that there may have been some noticeable variations during the study period. With a rise of X% year over year, 2016 saw the most remarkable growth rate. As a result, manufacturing peaked at X dollars per unit.

Global output growth lost momentum from 2017 to 2021 (Lu et al., 2018).

Major diseases of papaya

1. Damping-off
2. Foot rot of papaya
3. Anthracnose
4. Powdery mildews
5. Papaya ring spot disease
6. Papaya mosaic disease
7. Papaya leaf curls disease

Damping-off of papaya: Papaya is a commonly consumed fruit, valued for its affordable price and high nutritional content. In nursery beds, a disease known as damping-off can frequently be found affecting papaya seedlings. The infection spreads to the root system of the seedling, which ultimately leads to its demise. The stem tissues became brown and shrank, and water-soaked lesions occurred in the collar region. This led to the weakening of the tissues, and the seedling eventually died as a result. The damping-off disease that affects papaya seedlings can be caused by a variety of different species of the fungus *Pythium ultimum*, *Phytophthora parasitica*, *Fusarium solani*, and *Rhizoctonia*. Numerous soil-borne fungi from more than a dozen different genera including oomycetes (*Pythium* and *Phytophthora*), as well as some seed-borne fungus, have been implicated in recent reports of crop blight in a wide range of different crops. The majority of these viruses can potentially spread through both non-human and human activities, such as irrigation or stormwater runoff, because they are found in agricultural soils (Zappia et al., 2014). The introduction of diseased plants (especially seed-borne diseases), inadequate disinfection of greenhouses, and the use of contaminated irrigation water can all contribute to soil contamination. Other causes of soil contamination include improperly cleaned instruments.

Causal organism of damping-off of papaya: The damping-off disease, which can be brought on by a number of fungi including *Pythium ultimum*, *Phytophthora parasitica*, *Fusarium solani*, and *Rhizoctonia* species, can affect papaya seedlings.

Symptoms of damping-off: Damping-off symptoms might appear at any moment between seeding and the fourth week following sowing (TATAGIBA et al., 2025). Depending on when they first manifested, the disease's symptoms can be split into two distinct stages. Before the plant appears, the seed begins to decay, which is the first stage. This may occur before to seed germination or (ii) when biotic stress kills germination-stage seeds while shoot tissue is still in the ground. As the illness worsens, these lesions turn reddish-brown, brown, or black. Young stems can be swiftly weakened by enlarging lesions. Before emerging, seedlings may wither and die. Random pockets of poor emergence are an overall sign of pre-emergence dampening.

Pre-emergence symptoms: When the seeds are burned before the plant departs, they become visible. Before the seeds germinate, or (ii) when the germicidal seeds are killed by biotic stress while the shoot tissue is still in the ground, either of these scenarios may take place. The seed is too soft and difficult to grow in the first scenario. The germinated seeds are slain in the second scenario. The second situation involves distinctive water-injection lesions that occur at or below the soil line and harm tropical seeds (TATAGIBA et al., 2025). Lesions that are red, brown, or black can turn dark as the condition worsens. Young, fragile stems are girdled by constantly growing lesions extremely quickly. Before emerging, seedlings may wither and die. Low seedling emergence is typically found in isolated.

Post-emergence symptoms: When seedlings degrade, wilt, and ultimately die after emerging, this condition is known as post-emergence damping-off (TATAGIBA et al., 2025). Within every given seedling population, there will typically be a loss of at least a few seedlings. The seedlings may develop stem lesions at ground level and may die in clusters that are roughly round in shape due to a soil-borne disease. It is possible for seedling stems to grow thin and tough (a condition typically referred to as "wirestem"), which frequently results in decreased seedling vigour. These symptoms may also be followed by leaf spots, and it's possible that the root system will rot completely. Generally, the symptoms that appear on the roots of the seed include water-soluble, subcutaneous wounds that occur at or slightly below the surface of the earth and sometimes below the ground (i.e. on the roots). The plant can be high, dark.

Management of damping-off disease of papaya: To prevent the spread of damping off, a number of preventative steps should be taken, beginning with the selection of a suitable location for the establishment of the nursery. This location should be well ventilated, free from flooding, sunny, away from roads and papaya fields, and have irrigation water, all of which should be carried out in accordance with construction technical recommendations (Namsi et al., 2025).

Disease Life Cycle of Damping-Off of Papaya Caused by *Fusarium oxysporum*

Primary Source of Inoculum: *Fusarium oxysporum* survives in soil and infected plant residues as **chlamydospores**, which are resistant structures enabling long-term persistence. It can also be transmitted through contaminated or infected papaya seeds (Sharma & Gupta, 2019; Mbasa et al., 2025).

Survival: The pathogen remains viable in the absence of the host for several years due to chlamydospores in the soil. Crop residues, infested nursery beds, and weeds also serve as reservoirs (Nelson, 2018; Mishra et al., 2021).

Dispersal and Spread: Dissemination occurs through irrigation water, nursery tools, wind, and rain splash, which transport conidia and infested soil particles.

Contaminated seeds further facilitate long-distance spread (Khan et al., 2020b; Fravel et al., 2003).

Germination and Infection: Under favorable environmental conditions (warm temperatures 25–30 °C, moist soils, and high humidity), chlamydospores germinate and produce hyphae. These penetrate papaya roots and the collar region either directly or via natural openings and wounds (Patel et al., 2018; Alabouvette et al., 2009).

Colonization: The fungus colonizes the cortical and vascular tissues, obstructing water and nutrient movement. This leads to pre- and post-emergence damping-off symptoms (Iqbal et al., 2021; Gordon, 2017).

Symptoms Development

Pre-emergence damping-off: Seeds decay or fail to germinate due to fungal invasion.

Post-emergence damping-off: Seedlings emerge but show water-soaked lesions, root rot, stem constriction at the collar region, wilting, and collapse (Naz et al., 2019; Hussain et al., 2023).

Secondary Spread: Infected seedlings and infested soil release conidia and chlamydospores that infect nearby healthy seedlings, often causing patchy mortality in nurseries (Kumar et al., 2021; Memon et al., 2016).

Figure. 1

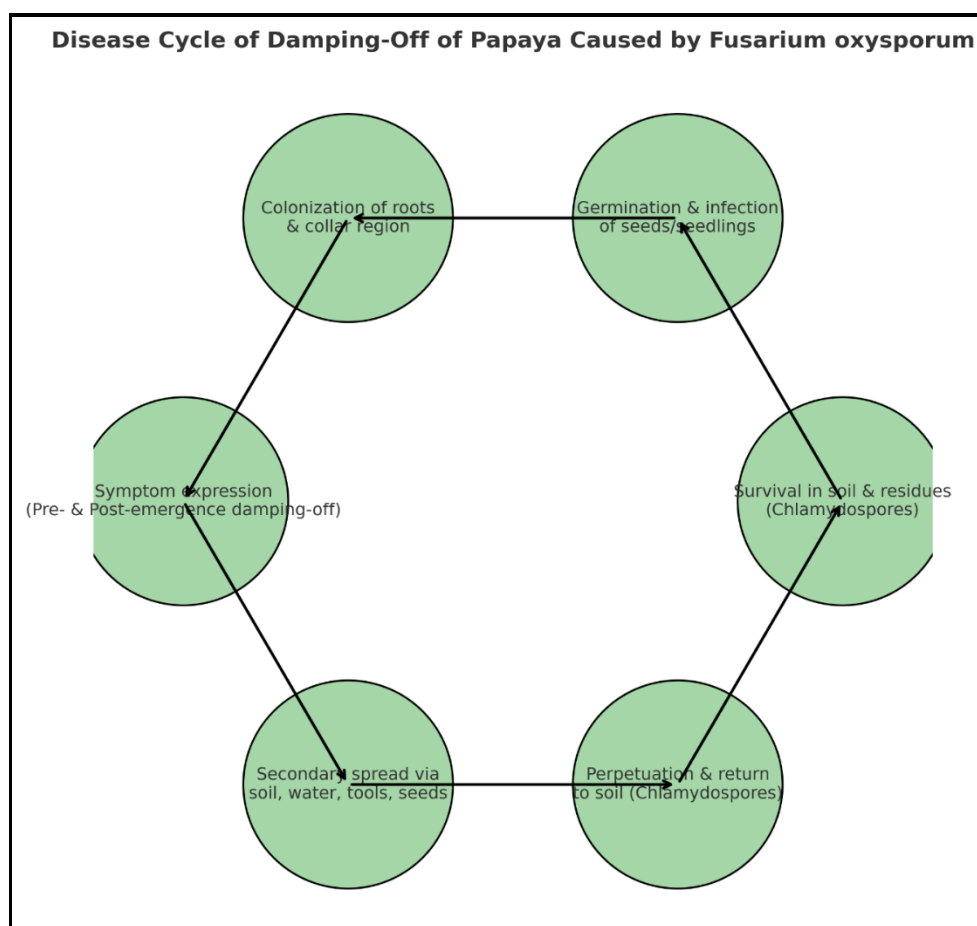


Figure.1. Disease Life Cycle of Damping-Off of Papaya Caused by *Fusarium oxysporum*

Perpetuation of Damping-Off of Papaya Caused by *Fusarium oxysporum*: The perpetuation of damping-off in papaya is largely attributed to the remarkable survival ability of *Fusarium oxysporum* in soil and plant debris. The pathogen produces thick-walled chlamydospores, which enable long-term persistence in the absence of a host. These structures can survive in soil for many years, even under unfavorable conditions, making eradication extremely difficult (Mbasa et al., 2025; Nelson, 2018).

Crop residues, decaying papaya roots, and infested nursery beds act as continuous sources of inoculum, ensuring disease recurrence in subsequent crops

(Sharma & Gupta, 2019). Infected or contaminated seeds also serve as a means of survival and long-distance spread of the pathogen (Khan et al., 2020a). The pathogen can remain latent in nursery soils, colonizing weeds and alternative hosts without causing obvious symptoms, thereby maintaining inoculum potential (Gordon, 2017; Mishra et al., 2021).

At the end of the growing season, diseased seedlings and crop residues become incorporated into the soil, where the fungus reconverts into chlamydospores, closing the disease cycle. This continuous cycle of survival, infection, and re-establishment explains the difficulty in managing damping-off of papaya through

conventional practices. Therefore, disease perpetuation is primarily soil-borne, residue-borne, and seed-borne, and requires integrated management approaches to break the cycle.

Cultural Control of Damping-Off in Papaya:

Cultural control is one of the most practical and eco-friendly approaches to reduce damping-off incidence in papaya nurseries. Once *Fusarium oxysporum*, the causal agent, is identified, existing agronomic practices can be modified to create conditions unfavorable for the pathogen and favorable for healthy seedling growth. The impact of biotic stressors can be minimized by employing methods that shorten the critical period between seed germination and seedling emergence, thereby reducing the window of vulnerability to infection (Agrios, 2005; Singh et al., 2018).

Most damping-off pathogens are relatively weak and require conducive environmental conditions to infect seedlings. Therefore, the severity of damping-off is largely influenced by seedbed preparation, soil pH regulation, sowing date and depth, plant density, moisture management, and pesticide exposure (Sharma & Gupta, 2019). For example, well-drained and solarized nursery soils significantly suppress pathogen populations and enhance seedling vigor (Patel et al., 2018). Adjusting sowing dates to avoid periods of high soil moisture and moderate temperatures can also lower infection risk. Additionally, maintaining proper spacing reduces canopy humidity and soilborne inoculum buildup, while balanced fertilization strengthens seedling resistance (Gordon, 2017; Mishra et al., 2021).

Overall, cultural practices form the foundation of integrated disease management. While they may not completely eliminate *Fusarium oxysporum*, their adoption reduces inoculum pressure and enhances the effectiveness of biological and chemical measures, making them essential for sustainable damping-off control in papaya.

Biological Control of Damping-Off in Papaya: The limitations and risks associated with chemical fungicides have led to an increased emphasis on biological control as a sustainable alternative for managing damping-off of papaya caused by *Fusarium oxysporum*. Excessive and indiscriminate fungicide use has raised concerns about environmental contamination, non-target effects, pesticide resistance, and potential health hazards (Bourguet & Guillemaud, 2016; Lamichhane et al., 2016). Resistance development in pathogens has further increased the likelihood of control failures, putting farmers at risk of economic losses (Onstad, 2013). Additionally, chemical fungicides may cause phytotoxic effects on seedlings, further limiting their safe use.

Biological control agents (BCAs) such as antagonistic fungi and bacteria have proven to be effective, eco-friendly alternatives. Among them, *Trichoderma* spp. (e.g., *T. harzianum*, *T. viride*), *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Streptomyces* spp. are

well-documented for their ability to suppress *Fusarium oxysporum* through mechanisms including mycoparasitism, antibiosis, competition for nutrients and space, and induction of systemic resistance in plants (Howell, 2003; Vinale et al., 2008; Iqbal et al., 2021).

For example, *Trichoderma harzianum* has been shown to inhibit the mycelial growth of *Fusarium oxysporum* by more than 70% under in-vitro conditions and significantly reduce damping-off incidence in papaya nurseries (Hussain et al., 2023). Similarly, *Pseudomonas fluorescens* produces antibiotics and siderophores that not only suppress the pathogen but also enhance plant vigor (Kumar et al., 2021). Unlike fungicides, these BCAs improve soil health, promote seedling growth, and contribute to long-term disease suppression without adverse environmental impacts.

Therefore, biological control represents the most eco-friendly and sustainable management strategy, especially when integrated with cultural practices. Its adoption can reduce chemical dependency, safeguard environmental quality, and ensure sustainable papaya production

Essential oil against *Fusarium oxysporum*:

The ability of seven plant essential oils to prevent *Fusarium proliferatum* and *Fusarium verticillioides* growth was examined. The lowest inhibitory and fungicidal concentration of essential oils was determined by measuring the fungicidal activity using the microtiter plate test. *Mentha arvensis* essential oil was shown to have the highest levels of fungicidal action, with *Thymus vulgaris* and *Anethum graveolens* essential oils coming in close behind. The oils of *M. arvensis* and *T. vulgaris* also showed a considerable inhibitory efficacy in the agar disc diffusion assay. The major components of the essential oil from *M. arvensis* were found using gas chromatography/mass spectrometry to be menthol (63.18%), menthone (15.08%), isomenthyl acetate (5.50%), and limonene (4.31%). The essential oil of *M. arvensis* showed significant antifungal activity against *F. proliferatum* and *F. verticillioides* isolates, opening the way for its use as antifungal control agents (Kumar et al., 2016).

Botanical Extracts in the Management of *Fusarium oxysporum*:

Plant-derived extracts and essential oils are increasingly being recognized as viable, eco-friendly alternatives to synthetic fungicides for the management of soil-borne pathogens, including *Fusarium oxysporum*, the causal agent of damping-off in papaya. Many plant-based formulations exhibit strong antifungal properties through mechanisms such as membrane disruption, inhibition of spore germination, interference with enzymatic activity, and induction of host resistance (Pawar & Thaker, 2007; Koul et al., 2008).

In controlled studies, soils artificially infested with *F. oxysporum* f. sp. *chrysanthemi* were treated with aqueous emulsions (1%, 5%, and 10%) of clove (70%

clove oil), neem (90% neem oil), pepper/mustard (chili pepper extract and mustard oil), and cassia (cassia extract), compared against the commercial fungicide Banrot. Results revealed that 10% aqueous emulsions of pepper/mustard, cassia, and clove extracts reduced the pathogen population density by 99.9%, 96.1%, and 97.5%, respectively, within three days of application compared to the untreated control. In contrast, neem oil extract unexpectedly increased the pathogen population density at all tested concentrations, while Banrot failed to significantly reduce pathogen levels (Bowers & Locke, 2000). Other studies have also highlighted the antifungal potential of garlic, eucalyptus, and turmeric extracts, which inhibited spore germination and mycelial growth of *Fusarium* spp. under in vitro conditions (Singh et al., 2018; Naz et al., 2019). These plant-based alternatives are biodegradable, safe for non-target organisms, and compatible with integrated disease management programs. However, variability in efficacy due to plant source, extraction methods, and concentration remains a limitation to their widespread adoption. Standardization, formulation improvements, and field validations are necessary to fully realize their potential as sustainable alternatives to chemical fungicides in papaya damping-off management.

Chemical Control of Damping-Off in Papaya: Chemical fungicides have long been the most widely employed method for managing soil-borne diseases).

such as damping-off caused by *Fusarium oxysporum*. Commonly used fungicides include mancozeb, which is effective against *Fusarium* and *Pythium*; itriazole and metalaxyl, active against *Phytophthora* and *Pythium*; benomyl and thiophanate-methyl, targeting *Fusarium* and *Rhizoctonia*; and captan, which provides broad-spectrum protection by reducing excessive soil wetness conditions conducive to damping-off (Agrios, 2005; Nelson, 2018). These chemicals often provide rapid and reliable control under nursery conditions.

However, increasing regulatory restrictions, particularly in the European Union, have significantly reduced the availability and use of several fungicides. Concerns about environmental pollution, pesticide residues, and human health risks have accelerated the phase-out of many active ingredients (Lamichhane et al., 2016). Furthermore, the emergence of fungicide resistance in *Fusarium* and other soil-borne pathogens has raised doubts regarding the long-term sustainability of chemical management strategies (Bourguet & Guillemaud, 2016; Brent & Hollomon, 2007).

While fungicides remain an effective short-term control option, their declining availability, regulatory pressure, and potential hazards underscore the need for integrated approaches. Thus, chemical control should be applied judiciously, preferably in combination with cultural, botanical, and biological methods, to ensure effective and sustainable management of damping-off in papaya.

Table 1. Comparative Efficacy of Different Control Strategies Against *Fusarium oxysporum* Causing Damping-Off of Papaya (reference)

Control Method	Examples	Efficacy (In-Vitro/Field)	Advantages	Limitations	Eco-Friendliness	Overall Suitability
Chemical Fungicides	Carbendazim, Difenconazole, Natio	Highly effective in inhibiting mycelial growth (80–100% in vitro) (Kumar et al., 2021)	Rapid action, reliable, easily available	Resistance risk, costly, environmental & health hazards	Low	Good for emergency outbreaks, not sustainable long-term
Botanical Extracts	Neem, Eucalyptus, Clove, Garlic	Moderate to high inhibition (40–75%) (Naz et al., 2019)	Safe, biodegradable, low-cost, farmer-friendly	Variable efficacy, needs higher doses, not standardized	High	Promising eco-friendly alternative, suitable for smallholder farmers
Biological Control Agents	<i>Trichoderma harzianum</i> , <i>Bacillus subtilis</i> , <i>Pseudomonas fluorescens</i>	High suppression of pathogen and growth promotion (60–90%) (Iqbal et al., 2021; Hussain et al., 2023)	Sustainable, improves soil health, induces resistance in plants	Slower action, sensitive to environmental conditions	Very High	Best eco-friendly and sustainable option
Cultural Practices	Soil solarization, crop rotation, sanitation, seed treatment	Reduces disease incidence by 30–60% (Patel et al., 2018)	Low-cost, preventive, improves overall nursery health	Not sufficient alone, labor-intensive	High	Essential baseline practice, should be combined with other methods

CONCLUSIONS

Damping-off of papaya, primarily caused by *F. oxysporum*, is a serious threat to papaya seedling production in Sindh Province and other papaya-growing regions. The infection leads to significant mortality in nurseries, resulting in reduced plant stand and economic losses for growers. The persistence of the pathogen in soil and plant debris, coupled with favorable nursery conditions such as high moisture and poor sanitation, makes management highly challenging.

Invitro studies have demonstrated that fungicides such as Carbendazim, Difenconazole, and Nativo are highly effective in inhibiting the pathogen. However, the indiscriminate and prolonged use of these chemicals poses risks of fungicide resistance, environmental contamination, and high production costs. Botanical extracts (e.g., neem, eucalyptus, clove, and thyme oils) have shown promising antifungal properties, while biological control agents such as *Trichoderma harzianum*, *Bacillus subtilis*, and *Pseudomonas fluorescens* have exhibited strong antagonistic activity and the added benefit of enhancing seedling vigor. These alternatives provide an environmentally safe and sustainable approach to disease management.

RECOMMENDATIONS

Integrated Disease Management (IDM): Adoption of IDM practices that combine cultural, chemical, botanical, and biological measures is essential for sustainable management of damping-off in papaya nurseries.

Cultural Practices: Emphasis should be placed on nursery sanitation, proper soil sterilization, optimum sowing density, and use of disease-free seeds to reduce pathogen pressure.

Fungicide Use: Chemical fungicides may be applied judiciously as a short-term solution or in severe outbreaks, preferably in rotation to minimize resistance development.

Botanical Extracts: Neem, eucalyptus, and clove extracts should be further standardized for large-scale nursery use as eco-friendly alternatives.

Biological Control: Mass multiplication and commercialization of effective bioagents such as *Trichoderma* and *Bacillus* strains should be encouraged for farmer adoption.

Research and Extension: Further research is needed to assess pathogen variability, disease epidemiology, and the field efficacy of combined treatments under Sindh's agro-ecological conditions. Extension efforts should focus on educating farmers about sustainable nursery practices and safe use of biocontrol options.

In conclusion, the successful management of papaya damping-off requires a shift from sole reliance on chemical control to integrated and eco-friendly approaches. Strengthening research-extension-farmer linkages will be crucial in reducing disease incidence

and ensuring sustainable papaya production in Sindh Province and beyond.

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