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Research Article

Management of Blue Mold Rot of Onion through Eco-Friendly Strategies

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ABSTRACT

Onion (*Allium cepa* L.) is a major vegetable crop widely cultivated and consumed globally, including in Pakistan. A systematic survey was conducted during 2022-23 in Sindh Province to record the incidence of blue mold disease. Diseased samples showing typical blue mold symptoms were collected for further analysis, and pathogenicity tests were performed to confirm the causal agent. For the *in vitro* experiment, different plant extracts, *Brassica juncea*, *Capsicum annuum*, *Coriandrum sativum*, *Mentha spicata*, and *Zingiber officinale*, were evaluated at three concentrations (4%, 8%, and 12%) against the mycelial colony growth of the pathogen. The *in vivo* trial was carried out using the most effective plant extracts to assess their efficacy in reducing rot severity (%) on onion bulbs. Among all surveyed districts, the highest disease incidence was recorded in Tando Allah Yar. The *in vitro* experiment revealed that *C. sativum*, followed by *Z. officinale* at 12% concentration, was significantly effective against the test fungus, showing mean mycelial growth inhibition of 76.29% and 71.88%, respectively. *M. spicata* also showed moderate inhibition (54.81%) at the same concentration, whereas *C. annuum* and *B. juncea* exhibited the least inhibitory effects compared to the others. The *in vivo* experiment demonstrated that *C. sativum*, followed by *Z. officinale*, was the most effective in reducing rot severity on onion bulbs, recording 31.00% and 44.33% severity, respectively, compared to 86.67% in the untreated control. It was concluded that *C. sativum* and *Z. officinale* extracts are effective and eco-friendly options for managing blue mold rot in onion.

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Introduction

Onion (*Allium cepa* L.), a member of the Amaryllidaceae family, is among the most widely cultivated and consumed vegetables worldwide. It plays a vital role in global cuisines, adding flavor to a variety of dishes, sauces, and soups. Onions are renowned for their characteristic pungent flavor and versatile culinary applications. In addition to their culinary importance, onions are highly valued for their nutritional and medicinal properties. They are rich in essential vitamins, particularly vitamin C, and minerals such as potassium and calcium. Moreover, onions contain several bioactive compounds, including flavonoids, sulfur-containing compounds, and antioxidants, which are reported to provide numerous health benefits such as improving cardiovascular health, enhancing immune function, and

reducing inflammation (Rai et al., 2016).

Often referred to as the "King of the Kitchen," onions impart a wide range of flavors to food. The phenolic and flavonoid compounds present in onions possess anti-inflammatory, anti-cholesterol, anti-cancer, and antioxidant properties. Regular onion consumption is believed to alleviate several ailments, including dropsy, kidney disorders, liver problems, heart disease, diabetes, and tuberculosis. Most onion cultivars contain approximately 89% water, 4% sugars, 2% fiber, 1% protein, and 0.1% fat, along with trace amounts of vitamins C and B6, folic acid, and other essential micronutrients (Prajapati and Patil, 2014).

Onions thrive across a wide range of climatic conditions, from temperate to subtropical regions, due to their high adaptability. They require adequate sunlight, moderate rainfall, and well-drained soils. Various onion cultivars have been adapted to specific environmental conditions, making onions a staple crop in both rural and urban farming systems, cultivated by smallholders and large-scale producers alike.

Pakistan ranks among the top onion-producing countries globally and within Asia. The country produces millions of tons of onions annually, contributing significantly to both domestic supply and export markets (Khan et al., 2020). Globally, onions are a key vegetable crop in countries such as Egypt, China, and India, where post-harvest losses significantly impact food security and farmers' income. Minimizing these losses is essential for enhancing farmer profitability, improving food availability, and reducing environmental waste (Mbohwa and Msimang, 2017).

According to FAOSTAT, (2019), Pakistan cultivates onions on approximately 135.1 thousand hectares, producing 1.763 million tons annually, making it a major national vegetable crop. The provinces of Sindh, Punjab, Balochistan, and Khyber Pakhtunkhwa (KPK) are key onion-growing regions, with Sindh being the leading producer due to its favorable climate characterized by warm temperatures and low humidity (FAO, 2023). Numerous onion varieties are cultivated in Pakistan, differing in color, shape, and storage capacity. Red onions are the most widely grown, particularly in Sindh, where the hot and dry climate is ideal for their production. Their strong flavor and compact bulb size make them popular for various culinary uses (Fakhar, 2020). Sindh remains one of the highest onion-producing regions in Pakistan, contributing a substantial share to the country's total production (Shah and Nawaz, 2022).

In agricultural commodities, post-harvest losses refer to the reduction in quantity or quality of produce between harvest and consumption. These losses are particularly critical for onions, one of the world's most consumed vegetables. Losses can occur during harvesting, handling, transportation, storage, processing, and marketing (Ahmed and Haque, 2022). During these stages, onions are especially prone to rotting due to fungal infections and other post-harvest pathogens (Nduwimana and Mugisha, 2019).

Among the major post-harvest diseases, black mold and blue mold rots are of particular concern, significantly affecting onion yield and storage longevity. Globally, about 35-40% of fruits and vegetables, including onions, are lost due to such post-harvest diseases, leading to severe economic losses (Gupta and Verma, 2002). Fungal growth, sprouting, and rotting accelerate onion decay and increase post-harvest losses. Furthermore, poor handling and inadequate transportation infrastructure exacerbate mechanical injuries and spoilage. Onions are highly sensitive to fluctuations in temperature and humidity during transit, which intensifies storage problems (Teng and Tan, 2020).

A survey conducted in Spain revealed that bulb rot in *Allium sativum* (garlic) was predominantly caused by fungal pathogens, with over 56% of samples exhibiting post-harvest rot. Several pathogens, including *Penicillium* spp., were identified after pathogenicity confirmation (Galvez and Palmero, 2021). Effective control of blue mold in stored onions and fruits depends largely on proper post-harvest management, particularly by maintaining optimal humidity and temperature to inhibit fungal growth (Wang et al., 2018).

Several biological control agents such as *Aureobasidium pullulans*, *Sporobolomyces roseus*, and *Cryptococcus luteolus* have demonstrated strong antagonistic effects against *Penicillium* species. Moreover, plant extracts such as *Aloe vera* (10%) and clove extract (10%) have shown significant antifungal activity in reducing infection caused by storage fungi (Mishra and Gupta, 2012). The application of plant-based extracts offers a promising eco-friendly and sustainable approach to managing *Penicillium* spp., the causal agent of onion blue mold. Various plant species, including clove, ginger, garlic, neem, thyme, oregano, cinnamon, and ginger, have exhibited potent antifungal activity under both *in vitro* and *in vivo* conditions (Sajid et al., 2023).

Considering the economic importance of onions and the significant losses caused by post-harvest blue mold rot, the present study was undertaken to explore eco-friendly management strategies for the effective control of this disease.

Materials and Methods

Survey at different markets/storage sites of onion

In the present study, a survey was conducted to record the incidence of blue mold rot disease of onion at various locations in Sindh. Samples of onion bulbs exhibiting typical symptoms of blue mold rot were collected from different sites and brought to the Plant Pathology Laboratory, Sindh Agriculture University, Tandojam, for further investigation.

A systematic survey was undertaken to assess the disease incidence in different markets and storage facilities across several districts of Sindh Province, namely Ghotki, Hyderabad, and Tando Allahyar, during 2022-2023.

Observations recorded

The disease incidence in each surveyed district was calculated using the following formula:

$$\text{Incidence } \% = \frac{\text{Number of infected onion bulb}}{\text{Total number of onion bulb}} \times 100$$

Isolation, multiplication, and purification of fungal pathogens

Isolation of the fungal pathogen was carried out from infected onion bulb samples following the protocol described by Schuck et al. (2014), using Potato Dextrose Agar (PDA) medium. The PDA composition was: potato starch = 20 g, dextrose = 20 g, and agar = 20 g per liter of distilled water (Johnson and Curl, 1972). Small sections were cut from the margins of symptomatic and healthy onion bulb tissues. Surface disinfestation was performed with 2% sodium hypochlorite solution for 2 min, followed by three rinses with sterile distilled water, and the tissues were dried on sterile filter paper.

Approximately four to five tissue pieces were placed in each autoclaved Petri plate (sterilized at 121°C, 15 psi, for 20 min) containing PDA medium. The inoculated plates were incubated at 26 ± 1°C with 85-100% relative humidity for up to 7 days. Actively growing fungal colonies were subsequently sub-cultured onto fresh PDA plates after 48 h of initial growth. The hyphal tip technique was employed repeatedly until pure fungal cultures were obtained.

Pathogenicity test

Pathogenicity tests were conducted to fulfill Koch's postulates. Fungal isolates that had previously produced characteristic disease symptoms on onion bulbs during the initial isolation were used for pathogenicity confirmation.

Asymptomatic, mature, and healthy onion bulbs were surface-sterilized with 1% sodium hypochlorite solution and rinsed three times with sterile distilled water. A 10 µl droplet of a single-spore suspension containing 10^6 conidia ml^{-1} of each fungal isolate was inoculated onto the sterilized bulbs using a micropipette. The spore concentration was determined using a Neubauer hemocytometer (Germany). Control bulbs were treated with 10 µl of sterile distilled water instead of the fungal suspension.

Spore suspensions were prepared using the same artificial medium that had been employed for the initial fungal isolation. After inoculation, the bulbs were incubated to allow disease development and later used to reisolate the fungal pathogens to confirm Koch's postulates (Sang et al., 2014).

Onion bulbs collected from the same districts were inoculated with their corresponding fungal isolates following the disinfection process. After surface sterilization with 1% sodium hypochlorite and rinsing three times with tap water, the bulbs were air-dried at room temperature to remove excess moisture. Each inoculated bulb was labeled, placed in a sterilized polythene cup, and sealed with aluminum foil. Control bulbs were treated in the same manner using only sterile distilled water.

The experiment was arranged in three replications per isolate. All inoculated and control bulbs were incubated at 25 ± 2°C in humid chambers maintained at 80 ± 10% relative humidity for 10 ± 2 days. Disease symptoms were observed periodically, beginning one week after inoculation. A standardized disease rating scale was used to assess the severity and virulence of blue mold rot on the inoculated onion bulbs.

In vitro experiment

Plant material selection, extraction, and dilution

In the present study, five indigenous plant species were selected for evaluation. Plant materials (leaves, rhizomes, and fruits) were collected and brought to the Fungal Plant Pathology Laboratory for further processing. The selection of plant materials was based on their reported antimicrobial potential and the presence of bioactive phytochemical compounds (Sathishkumar et al., 2014; Gebarowska et al., 2022). Details of the treatments, along with the selected plants and their respective parts, are provided in Table 1.

Table 1. Plant extracts and their concentrations used in the present study.

Treatment	Plant name	Botanical Name	Plant part	Concentration (%)		
T1	Mustard	*Brassica juncea*	Leaf	4	8	12
T2	Chilies	*Capsicum annum* L	Fruit	4	8	12
T3	Coriander	*Coriandrum sativum* L	Leaf	4	8	12
T4	Mentha	*Mentha spicata* L	Leaf	4	8	12
T5	Ginger	*Zingiber officinale*	Rhizome	4	8	12
T6	Control	-	-		0	

The collected plant materials were thoroughly washed with tap water followed by sterile distilled water to remove dust and debris. The samples were then air-dried at room temperature and ground into fine powder using a mechanical grinder. The powdered samples were properly labeled and stored for further use.

For extraction, 20 g of each powdered sample were placed in a conical flask containing 80% methanol (a total volume of 300 ml, comprising 240 ml methanol and 60 ml sterile distilled water). The flasks were placed on a magnetic stirrer at 24 ± 2°C for 4 h. After 48 h, the mixtures were filtered using Whatman No. 1 filter paper, followed by further purification with a 0.2 µm Millipore (nylon) membrane filter. The filtrates were then fan-dried in glass pans at room temperature to allow solvent evaporation and concentration of the extracts (Nortjie et al., 2022).

The residues obtained were considered 100% pure extracts, which were subsequently diluted to prepare different concentrations. The extracts were labeled and stored in a refrigerator until further use. To ensure complete recovery, dried residues adhering to the glass pans were carefully scraped off using sterilized surgical blades.

From the stock solutions, working concentrations were prepared at a ratio of 1:1 (1 g in 1 ml). For the poisoned food technique, plant extracts were incorporated into autoclaved growth media at final concentrations of 4%, 8%, and 12% (Al-Askar, 2012).

Application of plant extracts under *In vitro* conditions

To evaluate the effects of different selected plant extracts on the mycelial growth and growth inhibition (%) of the pathogen causing blue mold rot of onion, the food poisoning technique described by Balouiri et al. (2016) was employed. The treatments, as presented in Table 2, included plant extracts at concentrations of 4%, 8%, and 12%, each replicated three times.

Table 2. Effect of plant extracts on rot severity (%) in onion.

Treatments	Plant	Botanical Name	Plant part
T1	Coriander	*Coriandrum sativum* L	Leaf
T3	Ginger	*Zingiber officinale*	Rhizome
T4	Control	-	-

Considering that sterilization can alter the phytochemical composition of plant extracts, distilled water was used to dilute the extract powders. To preserve their bioactive compounds, the extracts were not autoclaved along with the medium; instead, they were added to the sterilized PDA after cooling to approximately 45-50°C. Furthermore, during the methanolic extraction process, the extracts were filtered through a 0.2 µm Millipore filter paper to ensure sterility.

Each plant extract was incorporated into the sterilized PDA at the designated concentrations (4%, 8%, and 12%) using a magnetic stirrer to ensure uniform mixing. The amended PDA was then poured into sterilized 90 mm Petri plates according to the respective treatment doses, with three replications per treatment. Control plates containing only PDA without plant extracts were also prepared. All plates were allowed to cool and solidify at room temperature.

A 5 mm mycelial disc from a seven-day-old fungal culture was aseptically placed in the center of each Petri plate using a sterilized cork borer. Control plates received the fungal disc under the same conditions. All inoculated plates were incubated at 26 ± 1°C. The radial mycelial growth was measured along two perpendicular diameters after seven days of incubation, once the fungal growth in control plates had completely filled the Petri dishes. The entire experiment was conducted under aseptic conditions.

Growth inhibition percentage

The mycelial colony growth of the test fungus was recorded after 7 ± 1 days, when the control plates were

fully covered with fungal mycelium. The average colony diameter was measured, and the percentage of growth inhibition in the treatments was calculated using the following formula (Yelmame et al., 2010).

$$\text{Growth inhibition \%} = \frac{Dc - Dt}{Dc} \times 100$$

Dc = Growth of fungal pathogen in control

Dt = Growth of fungal pathogen in treatment

Application of plant extracts on onion bulbs against rot severity (%) under *in vivo* conditions

Based on the *in vitro* evaluation, the two most effective plant extracts, *C. sativum* and *Z. officinale*, were selected for *in vivo* treatment in the present study. The experiment was conducted using the most effective concentrations of these extracts with three replications. Fresh, healthy, and uniform onion bulbs were selected for the study. Control bulbs were washed thoroughly under running water, surface-sterilized with 0.1% sodium hypochlorite solution for one minute, rinsed with sterile distilled water, and air-dried on sterile filter paper.

Stock solutions of the selected plant extracts were prepared to obtain the desired concentrations. A 12 µl aliquot of each extract was used for treating the onion bulbs, while the control bulbs were left untreated. The onion bulbs were dipped separately in the plant extract solutions for 5-7 minutes, whereas the control bulbs were dipped in sterile distilled water for the same duration. Each treatment was replicated three times. The treated bulbs were then shade-dried and placed in cardboard trays.

Spores were obtained from the sporulating margins of a 6 ± 1-day-old *Penicillium* culture using a sterile loop and suspended in sterile distilled water to prepare the spore suspension. The spore concentration was determined using a hemocytometer (Neubauer, Germany). After drying, the onion bulbs were marked and wounded at specific sites using the pin-prick method. Following wounding, a 10 µl aliquot of *Penicillium* sp. spore suspension (10^6 conidia/ml) was inoculated onto each injured site using moist sterile cotton swabs (Tripathi et al., 2007).

After inoculation, the bulbs were incubated at 26 ± 2°C and 80% relative humidity. Disease severity data were recorded after 11 ± 1 days of incubation.

Grading scale to evaluate the effect of plant extracts on rot severity (%) in onion bulbs

The effect of various plant extracts on onion bulbs was evaluated under storage conditions at room temperature. Data were recorded after 11 ± 1 days of incubation using a prescribed grading scale (0-5) as described by McKinney (1923). The mean rot severity (%) in onion bulbs was calculated using the following formula:

$$\text{Disease severity (\%)} = \frac{\text{Sum of all numerical rotting}}{\text{No. of onion bulbs examined} \times \text{maximum grade value}} \times 100$$

Table 3. Disease rating scale for calculating rot severity (%).

Grade	Extent of rotting	Numerical score (%)
0	No rotting	0
1	Pin head to 10mm	10
2	Up to 1/4th of the onion bulb	25
3	Up to ½ of onion bulb	50
4	Up to 3/4th of the onion bulb	75
5	More than 3/4th of onion bulb	100

Statistical analysis

The data recorded from the *in vitro* and *in vivo* experiments were analyzed using Analysis of Variance (ANOVA) under a Completely Randomized Design (CRD) at a significance level of $p < 0.05$. Mean comparisons were performed using the Least Significant Difference (LSD) test. The analyses were conducted using Statistix 8.1 software, and Microsoft Excel was used for data verification and calculation of mean and percentage values.

Results

Disease incidence of blue mold rot of onion

To determine the percentage incidence of blue mold rot of onion, a systematic survey was conducted during 2022-23. The results revealed that the disease incidence varied across different regions of Sindh, ranging from low to moderately high levels (Figure 1). Among all the surveyed districts, the highest mean disease incidence (45.1%) was recorded in Tando Allahyar, followed by Hyderabad with 34.3%. In Ghotki district, the mean disease incidence was 30.6%.

Pathogenicity

A pathogenicity test was conducted to fulfill Koch's postulates and to evaluate the virulence of pathogen isolates collected from different districts. All three isolates inoculated onto onion bulbs produced characteristic symptoms. Initially, white mycelial growth appeared on the surface of the bulbs, which later turned blue to bluish-

green, leading to bulb rot, typical of *Penicillium* spp. The re-isolated cultures were compared with the original isolates and found to be morphologically identical, confirming the pathogenicity of *Penicillium* spp.

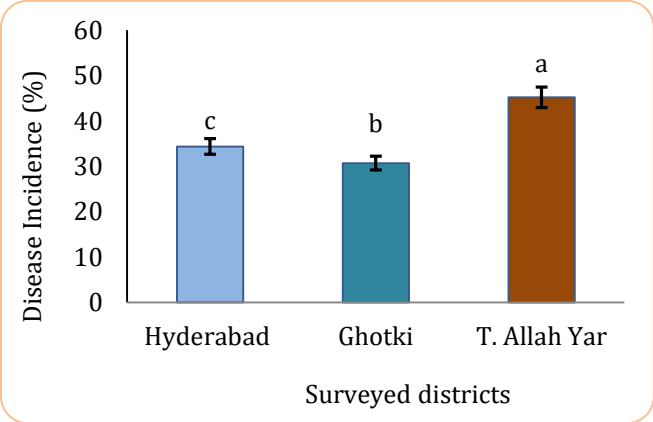

Figure 1. Mean disease incidence (%) of blue mold rot of onion in Sindh.

The rot severity (%) of each fungal isolate from different districts of Sindh was recorded on onion bulbs (Figure 2). Among the three isolates tested for virulence, the *Penicillium* isolate from Tando Allahyar exhibited the highest rot severity (85.33%), followed by the isolate from Hyderabad (49.67%), while the isolate from Ghotki showed comparatively lower rot severity (42.33%). These results indicate that the *Penicillium* spp. isolates varied in their pathogenic potential, with the Tando Allahyar isolate being the most virulent.

Evaluation of selected plant extracts against the mycelial colony growth of *Penicillium* sp. under *in vitro* conditions

An *in vitro* experiment was conducted to evaluate the efficacy of selected plant extracts against the mycelial growth of *Penicillium* sp. The results revealed that all tested concentrations of plant extracts exhibited varying degrees of inhibition compared with the control (Figure 3). Among the tested extracts, *C. sativum* showed the highest antifungal activity, followed by *Z. officinale*, at all concentrations. The 12% concentration of *C. sativum* extract was significantly most effective, reducing the mean radial colony growth of the pathogen to 21.33 mm, followed by *Z. officinale* with 25.3 mm. At 8% and 4% concentrations, the mean radial growths recorded were 35.0 and 46.0 mm for *C. sativum*, and 36.0 and 48.67 mm for *Z. officinale*, respectively.

M. spicata also exhibited notable inhibitory effects at the 12% concentration, recording a mean colony diameter of 40.67 mm, while 8% and 4% concentrations resulted in 52.0 and 60.67 mm, respectively. In contrast, *C. annuum* and *B. juncea* showed the least inhibitory effects at all tested concentrations (12%, 8%, and 4%), with mean mycelial growths of 63.33, 70.67, and 71.33 mm for *C. annuum*, and 70.0, 72.67, and 74.0 mm for *B. juncea*, respectively.

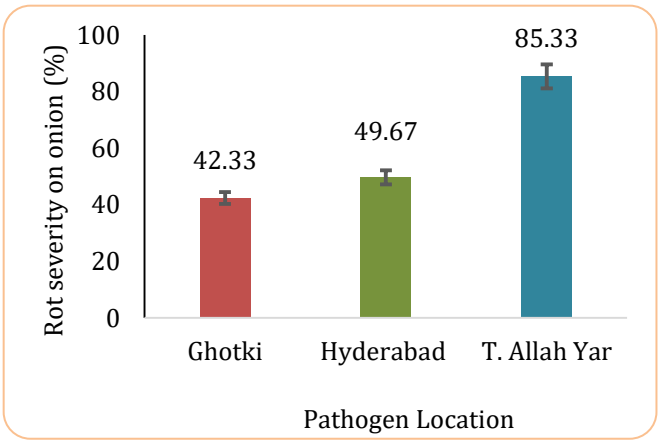

Figure 2. Virulence (%) of *Penicillium* spp. isolates in relation to rot severity (%) on onion bulbs.

***In vivo* assessment of plant extracts on the growth inhibition percentage of *Penicillium* sp.**

The study revealed that all concentrations of the tested plant extracts exhibited varying levels of effectiveness in inhibiting the radial mycelial growth of *Penicillium* sp. (Figure 4). The percentage of mycelial growth inhibition differed among plant extracts and showed a clear dose-dependent response.

Among all the tested extracts, *C. sativum* exhibited the highest inhibitory effect on the radial colony growth of the pathogen, followed by *Z. officinale*. At the highest concentration (12%), *C. sativum* and *Z. officinale* showed mean inhibition percentages of 76.29% and 71.88%, respectively. At lower concentrations of 8% and 4%, *C. sativum* recorded inhibition rates of 61.11% and 48.88%, while *Z. officinale* showed 60.00% and 45.92%, respectively.

M. spicata also demonstrated significant inhibitory activity, with a mean inhibition of 54.81% at 12%, and 48.14% and 34.07% at 8% and 4% concentrations, respectively. In contrast, *C. annum* and *B. juncea* exhibited the least inhibitory effects at all tested concentrations (12%, 8%, and 4%), showing mean inhibition percentages of 29.63%, 21.48%, and 20.74% for *C. annum*, and 22.22%, 19.25%, and 17.70% for *B. juncea*, respectively.

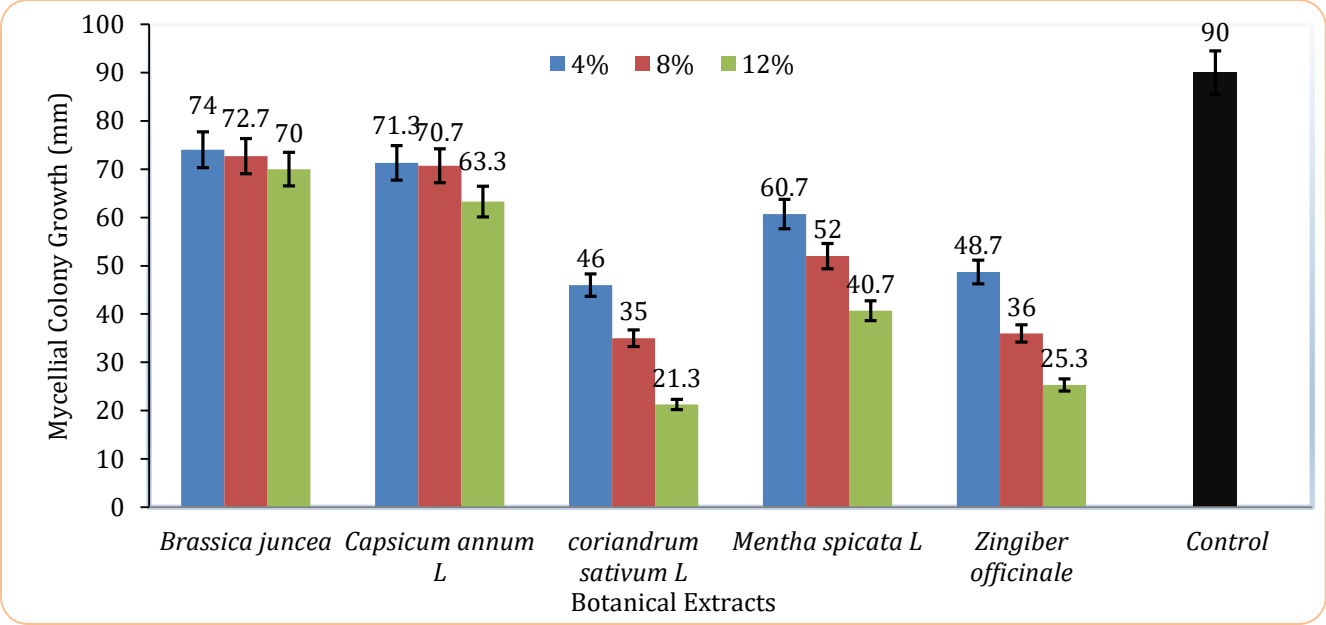

Figure 3. Mean radial mycelial growth (mm) of *Penicillium* sp. at different concentrations of plant extracts.

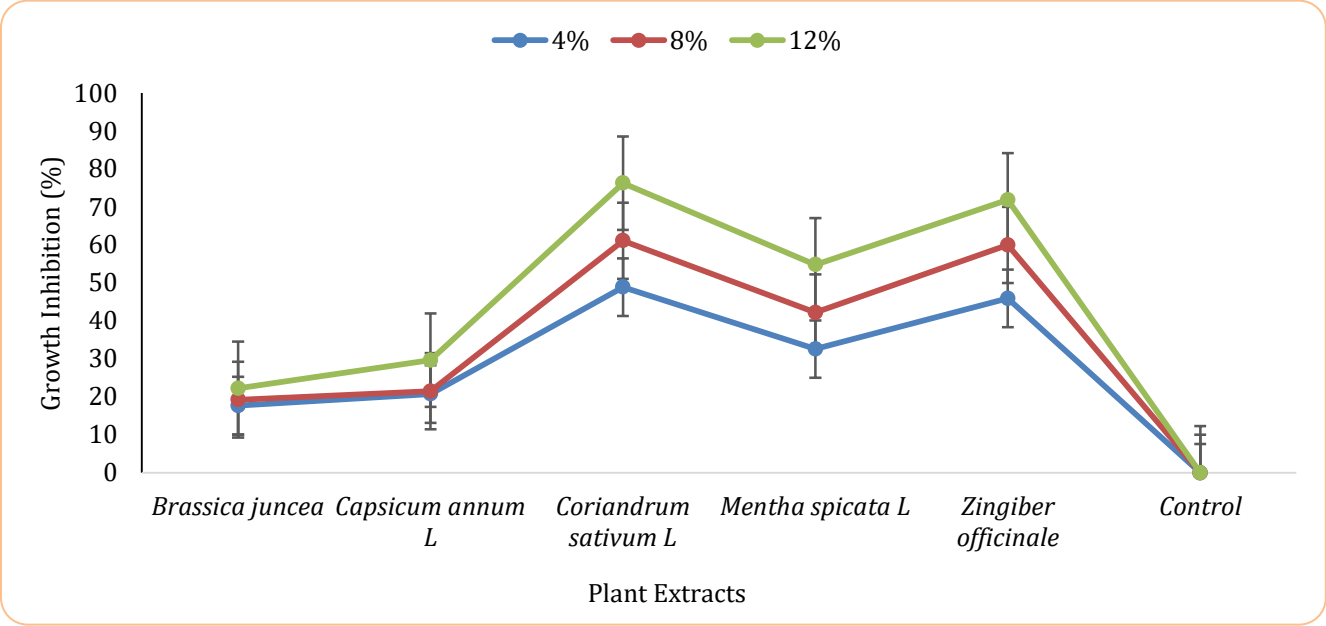

Figure 4. Inhibitory effects of plant extracts on the growth of *Penicillium* sp. at three concentrations (4%, 8%, and 12%).

Evaluation of plant extracts on onion bulbs for rot severity (%)

Experimental results revealed that the application of plant extracts significantly reduced the rot severity (%) on onion bulbs compared to the untreated control (86.67%), as shown in Figure 5. Among the treatments, *C. sativum* extract exhibited the greatest effectiveness, reducing rot severity to 31%, followed by *Z. officinale* extract, which resulted in 44.3% rot severity.

Discussion

Postharvest diseases significantly limit onion storage and marketability worldwide. Blue mold rot, caused by *Penicillium* species, is a major concern due to its severe impact on bulb quality, shelf life, and safety through mycotoxin contamination. The disease proliferates under high humidity and poor storage conditions. Although chemical fungicides are effective, their health and environmental risks highlight the need for eco-

friendly alternatives. Plant-derived bioactive compounds offer promising antifungal potential. The results of the present study are focused on blue mold incidence across regions, pathogenic variability, and the efficacy of selected plant extracts for its sustainable management.

Blue mold severely affects onion bulbs during storage, particularly in the El-Minia region of Egypt, where the disease reduces bulb quality and causes significant yield losses. Pathogenicity tests have confirmed that virulent isolates were recovered from infected samples collected from various storage sites (AboelAinin et al., 2024). Snini et al. (2016) also reported that blue mold, a common postharvest disease, leads to extensive rotting and deterioration of stored products, resulting in substantial economic losses due to both quality degradation and mycotoxin contamination.

Similarly, Moosa et al. (2022) observed that blue mold disease poses a major threat to postharvest storage, particularly in citrus fruits, causing severe decay and losses. These findings align with the current survey results, which revealed that the incidence of blue mold rot of onion was highest in Tando Allah Yar, followed by Hyderabad and Ghotki districts in Sindh. Moreover, virulent isolates of the pathogen causing blue mold rot were successfully recovered from infected onion bulbs collected from different locations.

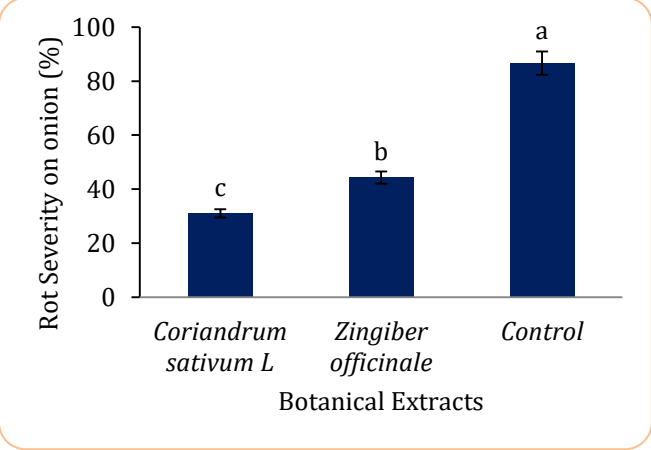

Figure 5. Mean rot severity percentage on onion bulbs treated with different fungicides against blue mold rot.

Lurwanu et al. (2025) studied the management of basal rot disease of onion using various concentrations of plant extracts and reported that *Z. officinale* at higher concentrations significantly inhibited the mycelial growth of the pathogenic fungus. Other plant extracts also showed varying degrees of antifungal activity. These findings support the results of the current study, suggesting that selected plant extracts at appropriate concentrations can effectively suppress the fungal pathogen responsible for basal rot of onion under *in vitro* conditions.

Comparable findings were reported by Pinto et al. (2010) and Elad et al. (2016), who demonstrated that plant extracts possess notable antifungal properties and can significantly inhibit the mycelial growth of pathogenic fungi. In the present study, *in vitro* evaluation of selected plant extracts at different concentrations revealed a substantial reduction in the radial mycelial growth of *Penicillium* sp. compared with the control. The antifungal efficacy was found to be concentration-dependent, with higher concentrations of *Z. officinale* extract exhibiting greater inhibition of fungal growth than lower concentrations.

As *Penicillium* species are well known for causing devastating postharvest losses in fruits and vegetables, there is an urgent need for eco-friendly antifungal alternatives to manage such pathogens effectively (Chen et al., 2025). In the current study, three concentrations of each plant extract were tested, and all showed varying levels of efficacy. Higher concentrations of *C. sativum* and *Z. officinale* extracts performed better than lower concentrations in inhibiting fungal growth and reducing disease severity. The superior antifungal activity of *C. sativum*, followed by *Z. officinale*, observed in the present study is consistent with the findings of other researchers.

Furthermore, Okigbo et al. (2018) reported that *Z. officinale* extract effectively controlled postharvest molds caused by *Penicillium* spp. and other fungal pathogens. These results are in agreement with the present study, indicating that *Z. officinale* extract possesses strong antifungal potential, making it a promising candidate for the management of blue mold rot of onion.

Conclusion

Among all surveyed districts in Sindh, the highest incidence of blue mold rot of onion was recorded in Tando Allah Yar (45.1%), while the lowest was in Ghotki district (30.6%). The *in vitro* and *in vivo* evaluations of plant extracts demonstrated significant antifungal activity. *Coriandrum sativum* and *Zingiber officinale* extracts effectively inhibited the mycelial growth of the test fungus by more than 70% under *in vitro* conditions and over 65% under *in vivo* conditions at the highest tested concentrations.

Based on these findings, *C. sativum* and *Z. officinale* extracts are recommended as eco-friendly alternatives for managing blue mold rot of onion. Further large-scale field experiments are suggested to validate these results and assess their potential for practical application in commercial onion storage and postharvest management systems.

Authors' Contributions

MAA conceived and designed the study; MW conducted all experiments, collected and organized the data for each experiment, performed statistical analyses, and prepared the initial draft of the manuscript; JDH provided supervision, technical guidance, and critical input throughout the research work; AAG reviewed and proofread the manuscript to ensure clarity and accuracy before submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 15: Life on Land

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