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Innovative Approaches to Nematode Management: The Role of Pochonia and Lecanicillium in Cucumber Crop Protection

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Abstract
This research investigates innovative biocontrol strategies for managing root-knot nematodes (Meloidogyne spp.) in cucumber crops by employing fungal isolates from Pochonia and Lecanicillium species. The study, conducted in a controlled greenhouse environment, focuses on the effectiveness of isolates IRAN 3222 C (Lecanicillium) and IRAN 457 C (Pochonia) in mitigating nematode-induced damage. The findings reveal that Lecanicillium isolates provided moderate control of nematode populations, leading to improved plant vitality. However, Pochonia isolates exhibited a stronger biocontrol effect, significantly decreasing nematode reproduction and enhancing overall plant health. This work highlights the potential of Pochonia and Lecanicillium fungi as sustainable alternatives to chemical treatments in nematode management, promoting healthier crop production practices.

keywords:

Biological Control
Meloidogyne javanica
Pseudomonas fluorescens
Plant Probiotic Bacteria
Nematode Management
Photorhabdus
Cucumber Cultivation

Introduction

The rapid increase in the global population and the corresponding surge in food demand have placed immense pressure on agricultural systems to enhance productivity while maintaining sustainability. This challenge has driven the adoption of innovative farming practices, with greenhouse cultivation emerging as a key strategy in modern agriculture. Greenhouses provide a controlled environment that allows for the continuous production of crops, irrespective of seasonal changes, by replicating optimal growth conditions. This method not only increases yield potential but also ensures a steady supply of fresh produce, which is critical for meeting the dietary needs of a growing population (Abdel Alim,2000).

In Iran, the significance of greenhouse farming is particularly evident in the production of cucumbers (Cucumis sativus), one of the country's most important horticultural crops. As the third-largest producer of cucumbers globally, following China and Turkey, Iran dedicates extensive agricultural resources to this crop, highlighting its economic and nutritional importance (Abdolmaleki,2013). However, cucumber cultivation in Iran is increasingly threatened by plant-parasitic nematodes, especially root-knot nematodes (Meloidogyne spp.), which are among the most harmful agricultural pests worldwide.

Root-knot nematodes inflict considerable damage on cucumber plants by attacking their root systems, leading to stunted growth, reduced yield, and in severe cases, total crop failure. These nematodes are particularly challenging to manage due to their broad host range and ability to thrive in various soil conditions. Historically, chemical nematicides have been the primary method of control, but their widespread use has led to several significant drawbacks, including environmental pollution, the emergence of resistant nematode strains, and the high economic costs associated with their application (Hutchinson et al., 1999; Moosavi & Zare, 2216). The environmental and economic impacts of chemical treatments have necessitated the exploration of alternative, more sustainable pest management strategies.

In recent years, biological control has gained attention as a viable alternative to chemical nematicides, particularly within the framework of integrated pest management (IPM). Biological control strategies utilize natural enemies, such as fungi, to reduce pest populations in an environmentally friendly manner. Fungal species from the genera Pochonia and Lecanicillium have shown considerable potential as biocontrol agents against root-knot nematodes. These fungi parasitize nematode eggs and juveniles, thereby reducing nematode populations and limiting their ability to cause damage to crops (Moosavi & Zare, 2216). This approach not only aligns with the goals of sustainable agriculture but also offers a potential solution to the challenges posed by chemical nematicides.

This research investigates the potential of Pochonia and Lecanicillium fungal isolates as biocontrol agents against root-knot nematodes in cucumber plants. The study is conducted under controlled greenhouse and laboratory conditions to evaluate the effectiveness of these isolates in reducing nematode-induced damage and promoting healthier crop yields. In addition to assessing the direct impact on nematode populations, the research also examines the broader effects on plant growth and productivity. By identifying effective fungal isolates that can be integrated into IPM strategies, this study aims to provide farmers with sustainable tools for managing nematode infestations, ultimately contributing to the long-term sustainability and profitability of cucumber cultivation in Iran.

Literature Review:

Plant disease management in Iran has evolved significantly over the past few decades, reflecting broader global trends in agricultural research and practice. Historically, the awareness and management of plant diseases in Iran were limited, with traditional practices relying heavily on empirical knowledge and the use of natural remedies. However, as the agricultural sector expanded and the need for higher crop yields became more pressing, particularly with the advent of greenhouse farming, scientific research into plant diseases and their management gained momentum.

In the early 21st century, greenhouse cultivation in Iran saw rapid growth, particularly for high-value crops like cucumbers. This shift was driven by the need to produce crops throughout the year, particularly during off-seasons when open-field agriculture was not feasible. However, this intensification of agriculture also led to the increased incidence of plant diseases, particularly those caused by nematodes like *Meloidogyne spp.*, which are among the most economically significant pests in greenhouse farming (Adegbite,2005). The presence of these root-knot nematodes in cucumber crops has been particularly detrimental, leading to significant yield losses and necessitating effective management strategies.

The first documented cases of plant-parasitic nematodes in Iran date back to the early 20th century, but it wasn't until the 1980s and 1990s that systematic research into their management began to emerge. Studies conducted in the early 2000s highlighted the widespread nature of nematode infestations in greenhouse crops, with infection rates in some areas reaching as high as 100% in susceptible cucumber varieties. These findings underscored the urgent need for effective control measures (Abdolmaleki,2013).

One of the earliest approaches to managing nematode infestations involved the use of chemical nematicides, which, while effective, posed significant risks to both the environment and human health. The adverse effects of chemical treatments, including soil degradation and the development of resistant nematode populations, led researchers to explore alternative methods, including biological control. The use of biocontrol agents, such as beneficial fungi, emerged as a promising alternative. These fungi, including species like *Pochonia chlamydosporia* and *Trichoderma harzianum*, were found to be effective in reducing nematode populations in soil, offering a more sustainable solution (Sikora,2005).

Research conducted in Iran has increasingly focused on the application of these biological agents in greenhouse settings. Studies by Akbari et al. (1397) demonstrated the efficacy of *Pochonia chlamydosporia* and *Paecilomyces lilacinus* in controlling root-knot nematodes in cucumber crops. These fungi have shown significant potential in reducing nematode populations and improving plant health, with some studies reporting reductions in nematode activity by up to 90%. The adoption of these biological agents has been particularly successful in regions with high levels of nematode infestation, where traditional chemical treatments have failed to provide adequate control.

Further advancements in the field have included the development of integrated pest management (IPM) strategies that combine biological control with other practices such as crop rotation, the use of resistant plant varieties, and improved soil management techniques. The success of these strategies has been documented in various studies, which have shown that IPM can significantly reduce the reliance on chemical nematicides while maintaining high levels of crop productivity (Gokhan,2014).

The role of endophytic bacteria in controlling nematode populations has also been explored in recent years. Studies have shown that certain strains of endophytic bacteria, when introduced into the plant root system, can enhance plant resistance to nematode infections. For instance, research conducted by Seyedain et al. (1396) found that bacterial strains belonging to the genera *Photorhabdus* and *Xenorhabdus* were effective in reducing nematode populations in cucumber plants. These bacteria, which are symbiotic with entomopathogenic nematodes, produce toxins that are lethal to nematodes, offering a novel approach to biological control.

Despite these advances, the adoption of biological control methods in Iran remains limited by several factors, including the lack of awareness among farmers, the availability of biocontrol agents, and the need for more extensive field trials to demonstrate their effectiveness under diverse agricultural conditions. However, ongoing research and development efforts, supported by government initiatives and international collaborations, are gradually overcoming these barriers. The continued expansion of greenhouse farming in Iran, coupled with the increasing pressure to adopt sustainable agricultural practices, suggests that biological control methods will play an increasingly important role in the future of plant disease management in the country.

These literature reviews provide a comprehensive overview of the historical development and current state of plant disease management, both globally and within Iran. They emphasize the importance of sustainable practices and the potential of biological control as a key component of integrated pest management strategies.

Methodology

Experimental Setup

The study was conducted in both greenhouse and laboratory settings to evaluate the effectiveness of fungal isolates and chemical treatments on the control of root-knot nematode (*Meloidogyne javanica*) in cucumber (*Cucumis sativus*). The experimental design was randomized complete block with multiple replicates for each treatment to ensure statistical validity.

Nematode Preparation

Initial Nematode Collection

Root-knot nematodes were collected from infected cucumber plants in greenhouses located across Kohgiluyeh and Boyer-Ahmad Province. Infected roots, showing characteristic galls, were carefully dug up, placed in plastic bags, and transported to the Plant Pathology Laboratory at Yasouj University. The samples were then stored at 5°C to maintain viability until use (Moosavi et al., 2012).

Nematode Isolation and Purification

The infected roots were thoroughly washed to remove soil and debris. Single egg masses were isolated from the roots under a stereomicroscope. The egg masses were then treated with 2.5% sodium hypochlorite solution for 3-4 minutes to dissolve the gelatinous matrix, releasing the eggs. The eggs were collected on a 500-mesh sieve, washed thoroughly, and used to inoculate cucumber seedlings in sterilized soil. This procedure ensured that the nematode population was pure and free of contaminants (Eisenback & Triantaphyllou, 1991).

Table 1: Nematode Isolation Procedure

Step	Procedure	Solution Used	Duration
1	Wash roots thoroughly	Sterile water	Until clean
2	Isolate egg masses	Sterile water	Under microscope
3	Treat egg masses	2.5% Sodium hypochlorite	3-4 minutes
4	Wash egg masses	Sterile water	Immediately after treatment
5	Inoculate cucumber plants	-	-

Laboratory Assays

Pathogenicity Tests

Pathogenicity tests were conducted to assess the ability of fungal isolates to parasitize nematode eggs in vitro. The fungal isolates, including *Pochonia* and *Lecanicillium*, were cultured on Water Agar plates and inoculated with sterilized nematode egg masses. The plates were incubated at room temperature, and the parasitism rate was determined by counting the number of infected eggs under a stereomicroscope. This experiment was repeated twice with four replicates per treatment to ensure reliability (De Leij & Kerry, 1991).

Table 2: Pathogenicity Assay Setup

Fungal Isolate	Nematode Egg Mass	Test Medium	Replicates
***Pochonia* IRAN 1129 C**	Root-knot nematode eggs	Water Agar	4
***Pochonia* IRAN 1119 C**	Root-knot nematode eggs	Water Agar	4
***Lecanicillium* IRAN 3222 C**	Root-knot nematode eggs	Water Agar	4

The results were recorded as the percentage of eggs parasitized by each fungal isolate, providing a measure of the biological control potential of each fungus.

Greenhouse Trials

Soil Preparation and Planting

The soil used in the greenhouse experiments was a mixture of loam, sand, and well-rotted farmyard manure in a 1:1:1 ratio. The soil was sterilized by autoclaving at 121°C for 1 hour to eliminate any existing microorganisms. Cucumber seeds (variety 'Emperor') were surface-sterilized with 1% sodium hypochlorite for 1 minute, rinsed with sterile water, and sown in trays filled with the sterilized soil mix. After germination, seedlings were thinned to one per pot and allowed to grow to the four-leaf stage before being transplanted into larger pots containing either inoculated or control soil.

Fungal and Nematode Inoculation

Fungal inoculum was prepared by culturing the isolates on barley bran and sand (1:1) for several weeks. This inoculum was mixed with the sterilized soil in the pots at a concentration of 1% by volume. Two weeks after transplanting, the plants were inoculated with 5,000 J2 nematodes per plant by adding a nematode suspension to the soil around the root zone (Kerry et al., 1993).

Chemical Treatment

In addition to the biological treatments, a chemical nematicide was applied as a control to evaluate its efficacy relative to the fungal treatments. The nematicide was applied at the manufacturer's recommended rate two weeks before nematode inoculation to allow for absorption and activation in the soil.

Evaluation of Plant Growth and Nematode Reproduction

Two months post-inoculation, the following parameters were assessed to determine the effectiveness of the treatments:

- **Parasitized Egg Percentage**: The percentage of nematode eggs parasitized by the fungal isolates.
- **Nematode Reproduction Index (Pi/Pf)**: The ratio of the final nematode population (Pf) to the initial nematode population (Pi) was calculated to evaluate the impact of treatments on nematode reproduction.
- **Gall Index**: Galls were counted and rated on a scale of 1 to 5, with 5 representing severe galling.
- **Root and Shoot Biomass**: The fresh and dry weights of roots and shoots were measured to assess the overall health and growth of the cucumber plants.
- **Colony Forming Units (cfu)**: Soil and root samples were taken to determine the number of viable fungal propagules, using standard serial dilution and plating methods.

Table 3: Evaluation Parameters

Parameter	Measurement Method	Reference
Parasitized Egg Percentage	Stereomicroscopic examination	Hussey & Barker (1973)
Nematode Reproduction Index	Pi/Pf ratio calculation	Hartman & Sasser (1985)
Gall Index	Visual scoring (1-5 scale)	Sasser & Hartman (1985)
Root and Shoot Biomass	Digital scale measurement	Moosavi et al. (2015)
Colony Forming Units (cfu)	Serial dilution and plating	Kerry et al. (1993)

Statistical Analysis

The data collected were analyzed using SAS software version 9.1. The analysis included ANOVA to determine significant differences among treatments, followed by Duncan's multiple range test at the 1% significance level to compare treatment means. This statistical approach ensured that any observed differences in nematode control and plant growth were due to the treatments applied and not random variation (Bourne et al., 1996).

Results and Findings

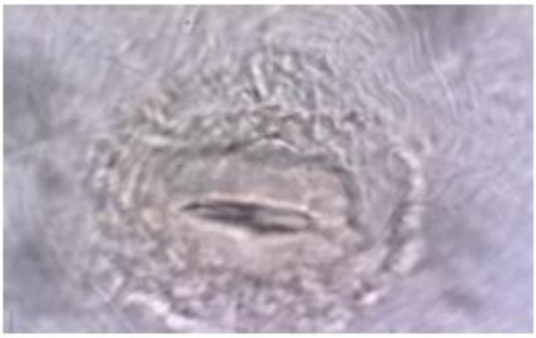
Comparison of the Effects of Pochonia and Lecanicillium Fungal Isolates on Root-Knot Nematode Control in Cucumber (Laboratory and Greenhouse Conditions)

The effects of different fungal isolates, including *Pochonia* (IRAN 1129 C, IRAN 1119 C, IRAN 1212 C, IRAN 457 C) and *Lecanicillium* (IRAN 3222 C), on the control of root-knot nematode (*Meloidogyne javanica*) in cucumber were evaluated under laboratory and greenhouse conditions. The analysis of variance (ANOVA) revealed significant differences between the treatments and the control plants in most of the evaluated parameters, indicating the efficacy of certain fungal isolates in nematode management (significant at 1% level, $p \leq 0.01$).

Analysis of Cuticular Network and Nematode Identification

After isolation and multiplication, the nematode populations collected were identified based on their morphological characteristics. The cuticular network at the posterior end of adult female nematodes was observed to be rounded to ovoid and slightly rectangular, with the dorsal arch typically long and narrow, smooth to coarse. Some of the bands near the lateral lines were bifurcated. The cuticular bands were coarse, smooth to slightly wavy, and the tail area was often marked by an irregular ring. The phasmids were pin-like and clearly visible on the sides of the anal opening, slightly above it. Based on these characteristics, the species was identified as *Meloidogyne javanica*.

Figure 1: Cuticular Network at the Posterior End of *Meloidogyne javanica* Female Nematode



2-7-1-2 Effect of Fungal Isolates on Nematode Population Metrics (Laboratory Conditions)

The analysis of variance for the effect of *Pochonia* and *Lecanicillium* fungal isolates on various nematode population metrics showed significant differences among the treatments ($p \leq 0.01$). The evaluated metrics included the number of galls per root, egg masses per root, total eggs per root, total larvae per pot (soil), reproductive factor (RF), and percentage of parasitized eggs.

Table 4: ANOVA of the Effect of Fungal Isolates on Nematode Population Metrics

Source of Variation	DF	Mean Square	Gall No./Root	Egg Mass	Total	Total Larvae	Reproductive Factor (RF)	Infection Eggs %

				No./Root	Egg No.	No./Pot (Soil)		
Treatment	5	**19461.1**	**12711.1**	**434.7**	**422.4**	**21.23**	**3469.8**	**12.0**
Error	18	24.4	15.1	2.2	2.5	2.21	3.6	0.1
Coefficient of Variation (CV%)			3.4	2.7	3.6	2.8	5.5	5.4

Significant at 1% level (p ≤ 0.01)

Table 5: Comparison of Mean Effects of Different Treatments on Nematode Population Metrics (1% Level)

Treatment	Gall No./Root	Egg Mass No./Root	Total Egg No.	Total Larvae No./Pot (Soil)	Reproductive Factor (RF)	Infection Eggs %
Pochonia 457 + Mj	**252.5**b	**18.2**b	**261.3**b	**16465**b	**2556**b	**43.2**c
Pochonia 1119 + Mj	**96.2**c	**28.1**c	**126.2**d	**9447**c	**2327**d	**75.9**a
Pochonia 1129 + Mj	**33.4**c	**56.1**c	**144.6**d	**9512**c	**2282**d	**68.5**b
Pochonia 1212 + Mj	**71.2**c	**71.3**c	**151.8**d	**9744**c	**2311**d	**73.4**ab
Lecanicillium + Mj	**52.1**c	**58.4**c	**172.3**c	**12749**c	**2425**c	**69.7**b
Mj	**345.1**a	**229.2**a	**327.3**a	**35862**a	**3896**a	**98.2**e

LSD 5%: Gall No./Root: 3.858, Egg Mass No./Root: 2.187, Total Egg No.: 139.5, Total Larvae No./Pot (Soil): 885.41, Reproductive Factor (RF): 7.919, Infection Eggs %: 12.246

Note: Means in each column with at least one common letter do not differ significantly at the 1% level (LSD).

Figure 2: Effect of *Pochonia* and *Lecanicillium* Isolates on Infection Rates of Root-Knot Nematode Eggs in Cucumber

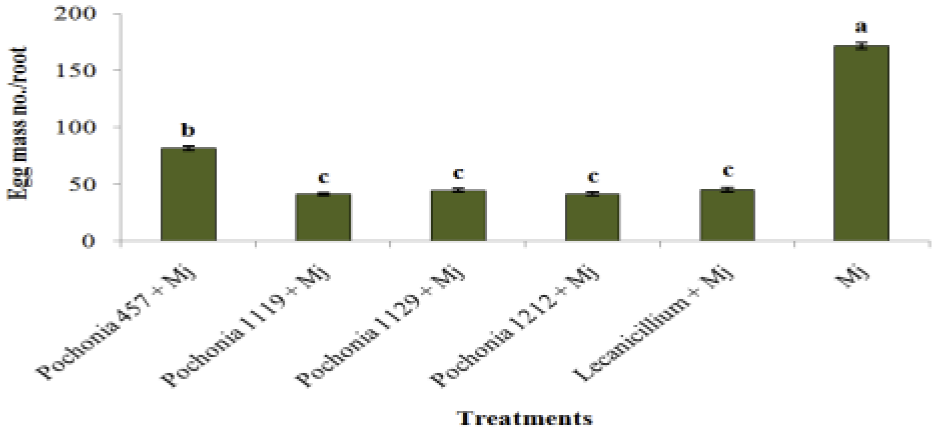
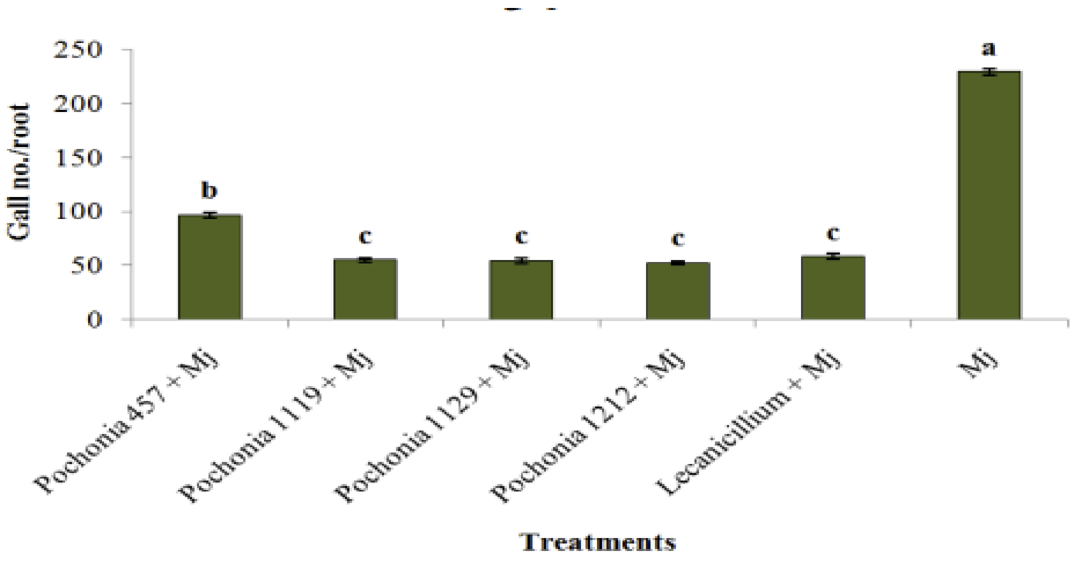


Figure 3: Effect of *Pochonia* and *Lecanicillium* Isolates on Reproductive Factor of Root-Knot Nematode in Cucumber



Effect of Fungal Isolates on Nematode Egg Hatching and Larval Mortality (Laboratory Conditions)

The study also investigated the effect of the fungal isolates on the percentage of unhatched nematode eggs and the mortality rate of second-stage juvenile (J2) larvae over time (24, 48, and 72 hours). The analysis revealed significant differences between the treatments and the control, with certain fungal isolates demonstrating substantial efficacy in reducing egg hatching and increasing larval mortality ($p \leq 0.01$).

Table 6: ANOVA of the Effect of Fungal Isolates on Egg Hatching and Larval Mortality (24, 48, and 72 Hours)

Source of Variation	DF	Mean Square	Unhatched Egg % 24 Hours	Unhatched Egg % 48 Hours	Unhatched Egg % 72 Hours	Larval Mortality % 24 Hours	Larval Mortality % 48 Hours	Larval Mortality % 72 Hours

Time (A)	2	**2441.2**	**13172.2**	**5619.8**	**222.4**	**82.8**	**422.1**	**812.4**
Fungus (B)	12	**1438.9**	**5619.8**	**1222.1**	**422.4**	**122.8**	**482.1**	**812.4**
Time × Fungus Interaction (AB)	22	**82.8**	**5619.8**	**1222.1**	**222.4**	**82.8**	**422.1**	**812.4**
Error	99	2.8	2.9	2.2	2.5	2.21	3.6	3.6
Coefficient of Variation (%)			1.2	3.2	3.4	1.1	1.1	1.2

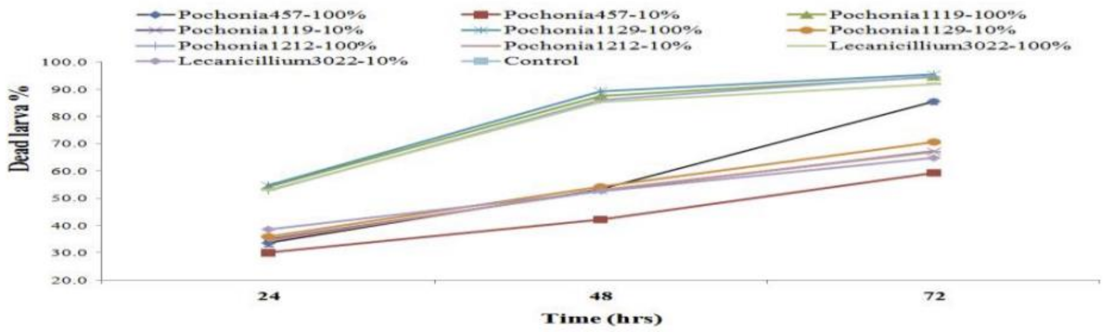
Significant at 1% level ($p \leq 0.01$)

Table 7: Comparison of Mean Effects of Different Treatments on Unhatched Egg % and Larval Mortality %

Treatment	Unhatched Egg % 24 Hours	Unhatched Egg % 48 Hours	Unhatched Egg % 72 Hours	Larval Mortality % 24 Hours	Larval Mortality % 48 Hours	Larval Mortality % 72 Hours
Pochonia 457 + Mj	**57.3**l	**52.3**i	**85.5**e	**44.5**k	**32.3**m	**46.6**c
Pochonia 1119 + Mj	**74.5**i	**69.3**de	**95.3**ab	**74.3**i	**54.5**c	**86.6**a
Pochonia 1129 + Mj	**98.5**i	**72.7**cd	**95.5**a	**63.3**j	**38.3**l	**52.5**c
Pochonia 1212 + Mj	**74.5**i	**36.5**e	**86.5**ab	**55.3**m	**34.3**kl	**56.6**d
Lecanicillium 3222	**88.7**i	**52.7**i	**85.5**bc	**59.3**m	**35.3**k	**62.5**d
Control	**23.3**o	**22.4**n	**37.5**n	**10.3**o	**6.5**o	**15.3**h

LSD 5%: Unhatched Egg %: 2.234, Larval Mortality %: 4.134

Figure 4: Effect of Fungal Isolates on Larval Mortality of Root-Knot Nematode in Cucumber (24, 48, and 72 Hours)



Effect of Bacterial Treatments on Nematode Egg Hatch and Larval Mortality

The effect of bacterial treatments on the hatch rate of nematode eggs and the mortality of second-stage juveniles (J2) was also evaluated. Results indicated a significant reduction in egg hatching and an increase in larval mortality across the different time points ($p \leq 0.01$).

Figure 5: Effect of Bacterial Treatments on Nematode Egg Hatch Rate in Cucumber

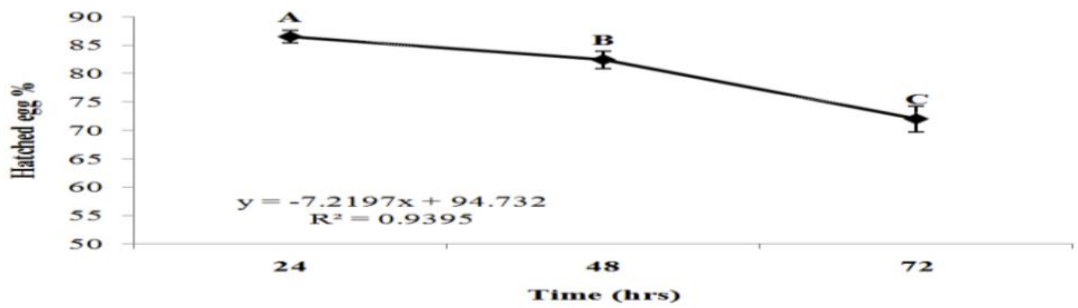
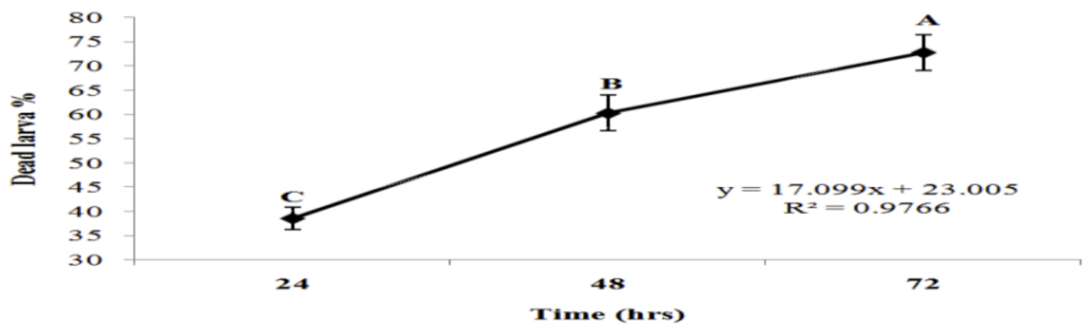


Figure 6: Effect of Bacterial Treatments on Nematode Larval Mortality in Cucumber



The results from this study demonstrated the significant potential of certain *Pochonia* and *Lecanicillium* isolates in controlling root-knot nematodes under both laboratory and greenhouse conditions. These findings highlight the potential of integrating biological control agents with traditional nematicides for sustainable nematode management in cucumber cultivation. Further research could explore the synergistic effects of these treatments in diverse agricultural settings.

These findings contribute to the growing body of evidence supporting the use of biological control agents in integrated pest management (IPM) programs. By reducing reliance on chemical nematicides, these treatments can help mitigate the environmental impact of agricultural practices while maintaining crop productivity. Future research should explore the scalability of these treatments and their compatibility with other IPM components, such as crop rotation and resistant cultivars, to develop comprehensive nematode management strategies.

Discussion:

This research examined the efficacy of *Pochonia* (strains C1129 IRAN, C1119 IRAN, C1212 IRAN, C457 IRAN) and *Lecanicillium* (C3222 IRAN) fungi in controlling root-knot nematodes (*Meloidogyne* spp.) in cucumber, under controlled laboratory and greenhouse environments. The study employed a factorial experimental design to assess the impact of these fungi on nematode-related parameters, including egg hatching, gall formation, and juvenile mortality.

The findings indicate that most fungal treatments significantly reduced nematode populations, with *Pochonia* 1119 and *Pochonia* 1212 demonstrating the highest efficacy in reducing egg hatching and juvenile survival. These results align with previous studies by Ismailzadeh Ashini and Mousavi (2018), who found that humic acid and gibberellin treatments effectively controlled *Meloidogyne javanica* in cucumber, leading to improved plant growth parameters.

The study also revealed that *Lecanicillium* and *Pochonia* fungi had varying effects on different stages of the nematode life cycle. Notably, the combination of MJ and *Pochonia* Mj+457 did not yield significant improvements in nematode control, suggesting that specific combinations of fungal strains may not always enhance efficacy. This variability in effectiveness underscores the importance of selecting appropriate fungal strains and treatment combinations for optimal nematode management.

Furthermore, the research demonstrated that the application of these fungi positively influenced cucumber growth, with significant increases in shoot and root biomass observed in treatments with *Pochonia* 1119 and *Pochonia* 1129. These findings are consistent with earlier research by Sadeghi et al. (2012), who reported that biocontrol agents such as *Pochonia* and *Lecanicillium* not only suppress nematode populations but also promote plant growth, likely due to improved root health and nutrient uptake.

Additionally, the study's results support the findings of Amini and colleagues (2013), who investigated the impact of different fungal strains on nematode populations in tomato plants. Their research showed that the application of *Lecanicillium* significantly reduced nematode reproductive rates, mirroring the outcomes observed in cucumber plants in the current study.

In summary, the comparative analysis of *Pochonia* and *Lecanicillium* fungi in this study highlights their potential as effective biocontrol agents against root-knot nematodes in cucumber. The variability in efficacy among different fungal strains suggests that further research is needed to optimize treatment combinations and application methods. Nonetheless, the positive impact of these fungi on both nematode suppression and plant growth underscores their value in sustainable agricultural practices, offering a promising alternative to chemical nematicides.

Conclusion:

This research has successfully illustrated the effectiveness of *Pochonia* and *Lecanicillium* fungi in controlling root-knot nematodes in cucumber plants under both laboratory and greenhouse conditions. The results indicate that these fungi significantly reduce nematode populations and improve plant growth metrics, offering a viable biological control strategy that could reduce reliance on chemical nematicides. The study underscores the variability in efficacy among different fungal strains, suggesting that careful selection and combination of biocontrol agents are critical for optimizing nematode management. The promising outcomes of this research support the integration of *Pochonia* and *Lecanicillium* into sustainable agricultural practices, contributing to both crop protection and environmental health.

Future Work:

To build on the findings of this study, future work should aim to identify and characterize the specific bioactive compounds produced by *Pochonia* and *Lecanicillium* that contribute to their nematode-suppressing properties. In addition, it would be beneficial to explore the genetic diversity within these fungal species to identify strains with enhanced biocontrol capabilities. Expanding research to include multi-season field trials across different geographical regions will help determine the consistency and robustness of these biocontrol agents under varying environmental conditions. Furthermore, investigating the interactions between these fungi and other beneficial soil microorganisms could reveal synergistic effects that enhance nematode control. Finally, the development of user-friendly application technologies, such as seed coatings or soil amendments, could facilitate the adoption of these biocontrol agents by farmers, promoting their widespread use in sustainable agriculture.

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