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Biocontrol potential of *Trichoderma* spp. compared with chemical fungicides against postharvest *Fusarium*-associated fruit rot of banana

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Abstract

Postharvest fungal rots of bananas contribute to significant losses of banana fruits during handling and storage. This research evaluated two native and two commercial *Trichoderma* treatments for the management of *Fusarium* fruit rot and compared their efficacy with four fungicides using dual culture and detached fruit assays. The dual culture assay showed that all *Trichoderma* treatments significantly inhibited mycelial growth of the pathogen. The detached fruit assays showed that *Trichoderma* T12 was the strongest *Trichoderma* treatment, which was statistically comparable to the best fungicide, Trifloxystrobin + Tebuconazole, in terms of lesion diameter. *Trichoderma* sp. (Ilami) was also statistically comparable to other chemical fungicides. Despite strong disease suppression, the *Trichoderma* treatments did not significantly increase the shelf life of the banana fruits under the given conditions. However, all the fungicides significantly delayed the ripening and extended the shelf life of the banana fruits under the given experimental conditions. The findings suggest that certain native *Trichoderma* isolates may provide disease control comparable to that of chemical fungicides, although their effects on fruit shelf life may be limited. Further research is needed to identify effective native isolates and validate their potential as biological alternatives to synthetic fungicides in specific pathosystems and storage conditions.

Keywords: Biological control, disease suppression, fungicide efficacy, native *Trichoderma*, postharvest disease, shelf life

1 Introduction

Banana is an important commercial crop, particularly grown in Nepal's tropical regions, with a significant impact on agricultural income and rural livelihoods[1,2]. According to the Ministry of Agriculture and Livestock Development (2026), Nepal produced 393,694 tonnes of bananas on 26,596 ha in the fiscal year 2024/25[3]. However, due to their climacteric nature, bananas are highly perishable and have a low shelf life under tropical ambient conditions because of rapid softening, senescence, and off-flavor development[4]. Physical damage during handling and transportation can further compromise fruit quality, while postharvest microbial infections, including fungal and bacterial pathogens, contribute to decay and reduce marketability and shelf life[5,6]. Bananas have high moisture content, which, combined with warm and humid conditions in tropical regions, makes the internal and external microclimate very well favorable for attack and colonization by fungal pathogens[7]. The post-harvest rots of banana include fruit rot, crown rot and cigar end rot and are associated with diverse fungal species belonging to *Colletotrichum*, *Lasiodiplodia*, *Musicillium*, *Ceratocystis*, *Nigrospora, Cladosporium*, *Acremonium*, *Penicillium*, *Neopestalotiopsis*, *Curvularia*, *Aspergillus*, and *Fusarium* genera. Among these, *Colletotrichum*, *Lasiodiplodia* and *Fusarium* species are the most important fungal pathogens causing rots in banana fruits[8–10]. Economically, fungal rots caused by these pathogens lead to losses of over 20% of fresh fruit, which shows a significant financial loss[11]. Moreover, *Fusarium* species associated with banana fruit rots, including *F. proliferatum* and *F. sacchari,* produce harmful mycotoxins, such as fumonisins and fusarin, which can contaminate the fruit and pose food safety risks, making *Fusarium* pathogens critically important[12,13].

Fusarium is commonly associated with crown rots in banana, but is also commonly reported to cause fruit rot[10,14,15]. *Fusarium* species originate in the field and persist through the postharvest supply chain, with physical injury and physiological disorders causing softening and deterioration of fruit tissues that lead to significant quality losses and reduced marketability[14,15]. Postharvest applications of synthetic fungicides have been the dominant control strategy for postharvest fungal rots in bananas. Fungicides such as thiabendazole, benomyl, imazalil, and bitertanol have been historically used by farmers to manage banana postharvest diseases, primarily through dipping or spraying harvested banana hands or treating cut crown surfaces[9]. Studies have also evaluated fungicides such as carbendazim, mancozeb, propiconazole, trifloxystrobin + tebuconazole, and carbendazim + mancozeb for managing banana fruit rot through preharvest sprays or postharvest dips[16,17].

However, repeated use of synthetic fungicides has led to the development of fungicide-resistant strains, reducing treatment effectiveness and raising major concerns. Fungicide residues in fruits also create food safety concerns. Furthermore, fungicide application can contribute to environmental contamination and limited acceptance in consumer markets[18,19]. These concerns have increased interest in alternative approaches to postharvest disease management, and therefore, bacterial and

fungal microbial antagonists are gaining attention[18]. *Trichoderma* species have been successful biological control agents (BCAs). These ascomycete fungi are found to suppress phytopathogenic fungi through different modes such as competition, mycoparasitism, and the production of antibiotic metabolites[20–22]. Furthermore, *Trichoderma* species can activate a plant defense system known as *Trichoderma*-induced systemic resistance (TISR)[21].

Different studies have evaluated *Trichoderma* species for their biocontrol potential against postharvest fungal rots in bananas. A study by Mortuza and Ilag (1999) reported that *T. viride* reduced fruit rot caused by *Lasiodiplodia theobromae*[23], while another study demonstrated that conidia and culture filtrates of *T. asperellum* suppressed banana fruit rots caused by multiple pathogens, including *Fusarium oxysporum*[24]. Sangeetha et al. (2009) found that individual isolates varied in their effectiveness against crown rot, but few significantly improved disease control singly and in combination[25]. Similarly, Alvindia and Acda (2012) investigated *T. harzianum* in combination with hot-water treatment for managing banana crown rot[26]. Another study reported that *T. asperellum* prr2 suppressed postharvest anthracnose and crown rot and improved banana shelf life under their experimental conditions[27].

Even though the potential of many species of *Trichoderma* for managing postharvest rots of bananas is well documented, the efficacy of these BCAs also varies with pathogen as well as *Trichoderma* isolates and environmental conditions. Therefore, the performance of native *Trichoderma* isolates cannot be assumed without direct evaluation. Furthermore, studies directly comparing the native *Trichoderma* isolates with commercial strains as well as common practices against postharvest *Fusarium* rot of banana fruits are limited, particularly in Nepal. Therefore, this study aimed to evaluate two native *Trichoderma* isolates against postharvest banana fruit rot and compare their efficacy against commercially available *Trichoderma* strains and commonly used fungicides by banana farmers of Tikapur.

2 Materials and Methods

2.1 Materials used

Banana fruits with fruit rot symptoms[28] were collected from a local farmer's field in Tikapur. Banana fruits (cv. Grand Naine) required for pathogenicity testing and detached fruit assays were also sourced from the local farmers (coordinates 28.51°N, 81.11°E). Potato dextrose Agar, Granulated (HiMedia Laboratories, Mumbai, India) and Agar Agar, Type I (HiMedia Laboratories, Mumbai, India) were used to prepare culture media. The chemical fungicides used were Carbendazim 12%+ Mancozeb 63% WP (SAAF, UPL Limited, Mumbai, India), Thiophanate methyl 70% WP (Vapcotop-70%, VAPCO Manufacturing CO. Ltd., Jordan), Tebuconazole 50% + Trifloxystrobin 25% WDG (Nativo, Bayer Crop Science, India) and propiconazole 25 % EC (Digest, Monsoon Agrochemicals Pvt. Ltd., Haryana, India). These chemical fungicides were selected based on discussions with banana farmers of Tikapur regarding their management practices. The chemical fungicides and two commercial formulations of *Trichoderma*, TreeDevi (*Trichoderma viride*, Yarsa Agro Research Pvt. Ltd.) and Ilami (*Trichoderma* sp., Ilami Agro & Tech Pvt. Ltd.), were purchased from a local agrovet shop. This experiment used two indigenous *Trichoderma* isolates, *Trichoderma* K25 and *Trichoderma* T12, preserved at the Nepal Plant Disease and Agro Associates, Balaju, Nepal.

2.2 Isolation and identification of the pathogen

Small tissue pieces were cut aseptically from the margin of the diseased area of the infected fruits, including both diseased and healthy parts. The tissue pieces were washed with sterile water to clean debris, followed by surface sterilization by dipping in 1% sodium hypochlorite for 1 minute and then rinsed three times with sterile distilled water. The sterilized tissues were dried on blotting paper in a laminar flow and incubated on water agar at 25±2 ℃. A small hyphal section of the fungal growth was cut and transferred to PDA plates and incubated under the same conditions[29]. Pure culture was obtained by cutting and transferring a single hyphal tip from the resulting colony to a new PDA plate[30]. The pathogen was identified based on its colony and microscopic characteristics from its culture on PDA and Carnation leaf agar (CLA)[31,32].

2.3 Pathogenicity testing

For pathogenicity testing, mature banana fruits of uniform size and free from visible wounds and disease symptoms were selected. The fruits were first washed with clean water, followed by surface sterilization by dipping in 1% sodium hypochlorite for 1 min and then rinsed three times with distilled water. The surface-sterilized fruits were dried on sterile blotting paper under aseptic conditions. Thereafter, four banana fruits were placed in a transparent box lined at the bottom with three layers of moist blotting paper, and four wet cotton balls were placed inside the box to maintain humidity. Two such boxes of four banana fruits were used: one for inoculated fruits and the other

for the control. Three equidistant wounds were made on each fruit using a sterile needle. A conidial suspension of 1×10^6 conidia mL^{-1} was prepared, and a 10 µL droplet of the suspension was inoculated into each wound using a micropipette. Control fruits were inoculated with an equal volume of distilled water. The inoculated and control fruits were incubated under dark conditions at 25 ± 2 °C. The fruits were regularly monitored until the wounded area of the fruit showed typical fruit rot lesions, and the same pathogen was reisolated from the same lesions to prove Koch's postulates of pathogenicity[33].

2.4 Dual culture assay

The antagonism and colony interaction between each *Trichoderma* strain and *Fusarium* sp. were evaluated using the dual culture method[34]. An 8 mm diameter mycelial plug of *Fusarium* sp. was placed 1 cm from the edge of the 90 mm petriplates containing about 20 mL of PDA. The plates were incubated at 25±2 ℃ in the dark for 48 hours to allow establishment of the pathogen due to its slow-growing nature relative to fast-growing *Trichoderma* species. After 48 hours, an 8 mm mycelial disc of *Trichoderma* treatment from an actively growing region of a respective 3-day-old *Trichoderma* culture was placed on the opposite side of the previously pathogen-inoculated Petri plates. The control plates were left with only the pathogen.

Each treatment was replicated seven times and incubated at 25 ± 2°C in the dark. Three plates inoculated with only *Trichoderma* and no pathogen were also kept for each treatment for reference. The radial growth of the pathogen was measured daily until its growth remained constant for two consecutive days, which occurred on the 8th and 9th days after inoculation. The percentage inhibition of *Fusarium* growth caused by each *Trichoderma* isolate was calculated for the 8th day after inoculation of *Trichoderma* using the formula adopted from[35]:

$$\text{Growth inhibition ratio (\%)} = \frac{\text{R1-R2}}{\text{R1}} \times 100$$

Where, R1 is the radial growth of the pathogen-only control, and R2 is the radial growth of the pathogen in the presence of the *Trichoderma* isolate

2.5 Detached fruit assay

The *Trichoderma* isolates were further tested for their disease control efficacy against *Fusarium* sp. under detached fruit assays. Four chemical fungicides commonly used by the banana farmers of Tikapur were also added as treatments to compare the efficacy of the *Trichoderma* isolates against *Fusarium* sp. The fungicide treatments included carbendazim + mancozeb, thiophanate methyl, propiconazole, and trifloxystrobin + tebuconazole. Fruits without treatment but inoculated with *Fusarium* sp. were maintained as the inoculated control, while fruits with no treatment and no pathogen were kept as the uninoculated controls. The fruits were surface sterilized using the above-mentioned techniques, and the respective treatments were applied to the fruits by dipping the

surface-sterilized fruits in the treatment suspension of either 10^6 conidia/mL for *Trichoderma* or 0.1% a.i. for the fungicides. The controls were dipped in sterile water. After dipping, the fruits were let dry on blotting paper under aseptic conditions. *Fusarium* sp. was inoculated 24 h after treatment application following the procedure described above in the Pathogenicity testing section. Lesion diameter was measured every 72 hours to assess disease development, and days to ripening and shelf life were also recorded to assess physiological changes. A fruit was considered ripe when the peel had turned completely yellow and softened to a stage considered ready for consumption. Shelf life was recorded as the number of days from treatment until the fruit became excessively soft and was considered unsuitable for consumption. The experiment was repeated twice, maintaining four replicates for each treatment in both experiments.

2.6 Data analysis

The data obtained from the research were systematically managed using Microsoft Excel 2024. All statistical analyses and graphical visualizations were done using R version 4.5.2. The data from the detached fruit assay were compared between the two experimental runs, and as no significant differences were detected between the runs, the data were pooled for statistical analysis, making 8 replicates per treatment. Mycelial diameter, lesion diameter, days to ripening, and shelf-life data were subjected to analysis of variance (ANOVA) under a completely randomized design for statistical analysis using the 'agricolae' package in R. Before ANOVA, the data were assessed for linear model assumptions using the 'gvlma' package. As the lesion diameter data did not meet the assumptions of ANOVA, they were natural log-transformed before being subjected to ANOVA. Treatment means were compared using Tukey's honestly significant difference (HSD) test at α=0.05. Disease progress over time was visualized using lesion diameter measurements recorded at successive intervals, and the area under the disease progress curve (AUDPC) was calculated to summarize overall disease development and presented as descriptive treatment means.

3 Results

3.1 Isolation and identification of the pathogen

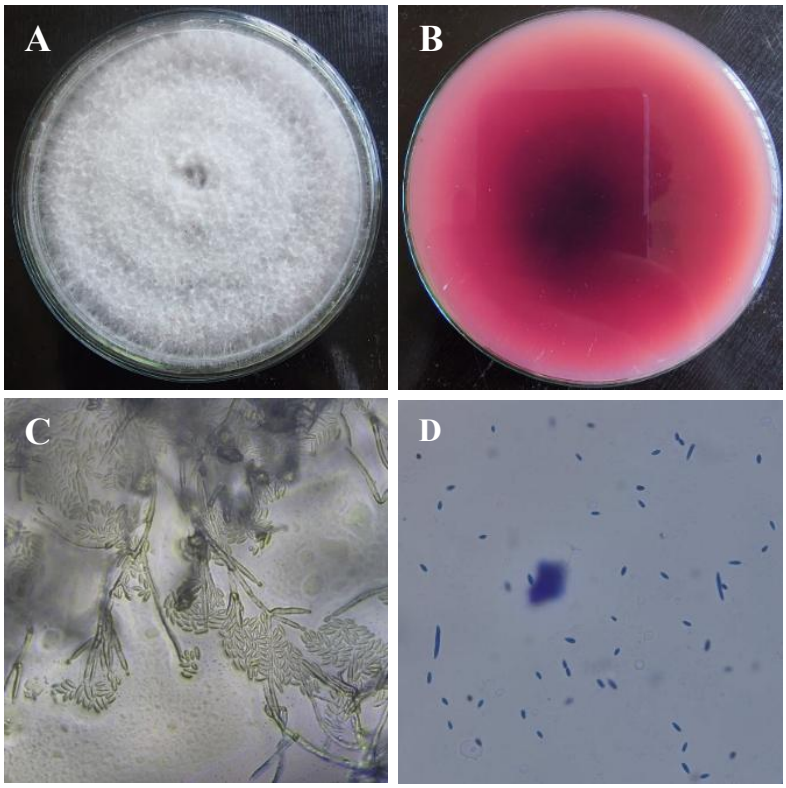


Figure 1 Morphological characteristics of the *Fusarium* sp. isolate: 9-day-old colony on PDA - front view (A); reverse view of the colony (B); microscopic view (400X) showing microconidia and phialides (C); micro- and macroconidia stained in lactophenol cotton blue solution (400X) (D)

The isolated fungal pathogen had a white to vinaceous aerial mycelium with vinaceous, wine-colored pigmentation on the reverse side of the PDA culture. The fungus produced abundant oval microconidia borne predominantly on monophialides and arranged on false heads (Fig. 1). Few macroconidia, more or less straight with an acute apical cell and up to 4 septa, were also observed in carnation leaf agar. We did not observe sporodochium and chlamydospores in either medium or fruit tissue.

3.2 Pathogenicity testing



Figure 2 Pathogenicity testing of *Fusarium* sp. in banana fruit; water-inoculated fruit (left), *Fusarium* conidia-inoculated fruit (right)

In the pathogenicity test, the fruit started showing dark lesions on the inoculated surface after 72 hours of inoculation (Fig. 2). The lesion then expanded gradually, forming necrotic lesions and gradually softening. The lesion surface also showed some mycelial growth under high humidity conditions. No such symptoms were shown by water-inoculated fruits. The same above-mentioned pathogen was reisolated from the symptomatic lesions, proving Koch's postulates of pathogenicity.

3.3 In vitro antagonistic assay

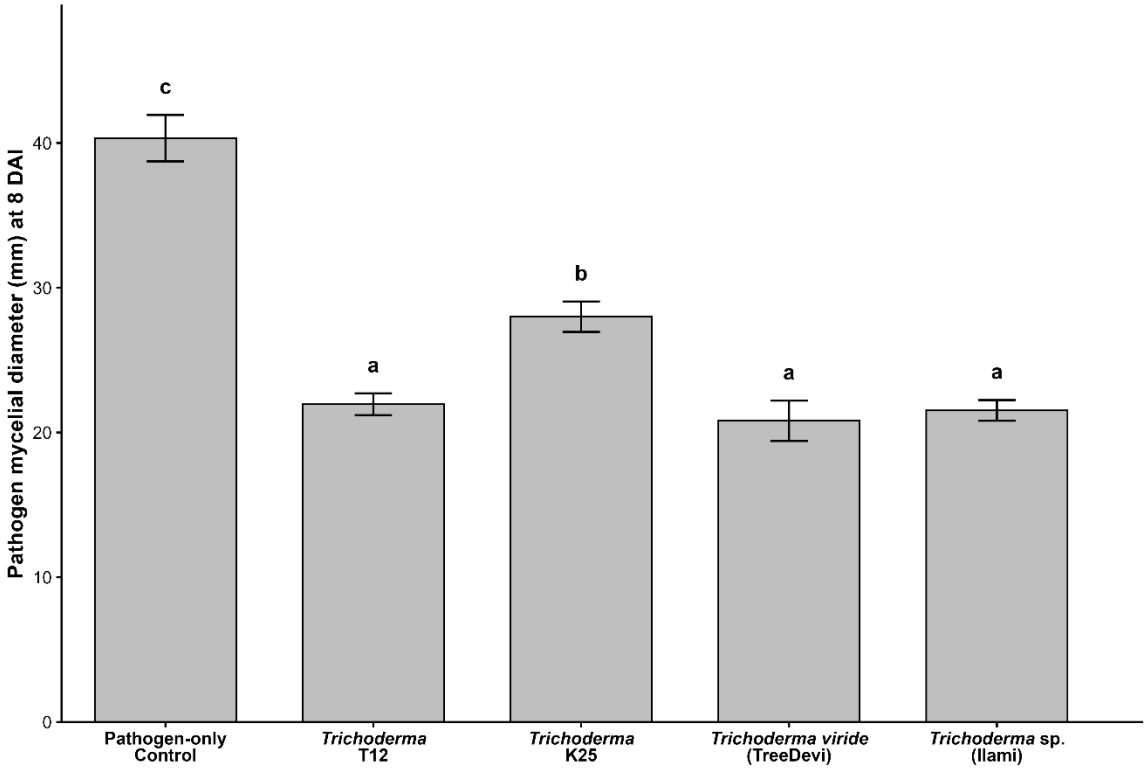


Figure 3 Radial colony growth of *Fusarium* sp. in a dual-culture assay with different *Trichoderma* isolates compared with the pathogen-only control after 8 days of incubation. Error bars represent the standard error (SE) of the mean for each treatment. Bold letters above the error bars indicate statistical groupings based on Tukey's HSD test ($P < 0.05$); treatment bars sharing the same letter are not significantly different from each other.

In the dual culture assay, the pathogen exhibited the greatest colony radius in the control (40.3 mm), whereas all *Trichoderma* treatments significantly reduced colony growth ($P < 0.001$). Among them, *Trichoderma* T12, *Trichoderma viride* (TreeDevi), and *Trichoderma* sp. (Ilami) showed greater inhibition of the pathogen, with an inhibition of 45.07%, 48.17% and 46.35% over the control, respectively. These isolates were statistically indifferent to each other. In contrast, *Trichoderma* K25 showed a comparatively lower antagonistic activity, recording a colony radius of 2.85 mm and 29.50% inhibition, and was significantly less effective than the other three isolates (Fig. 3 & 4).

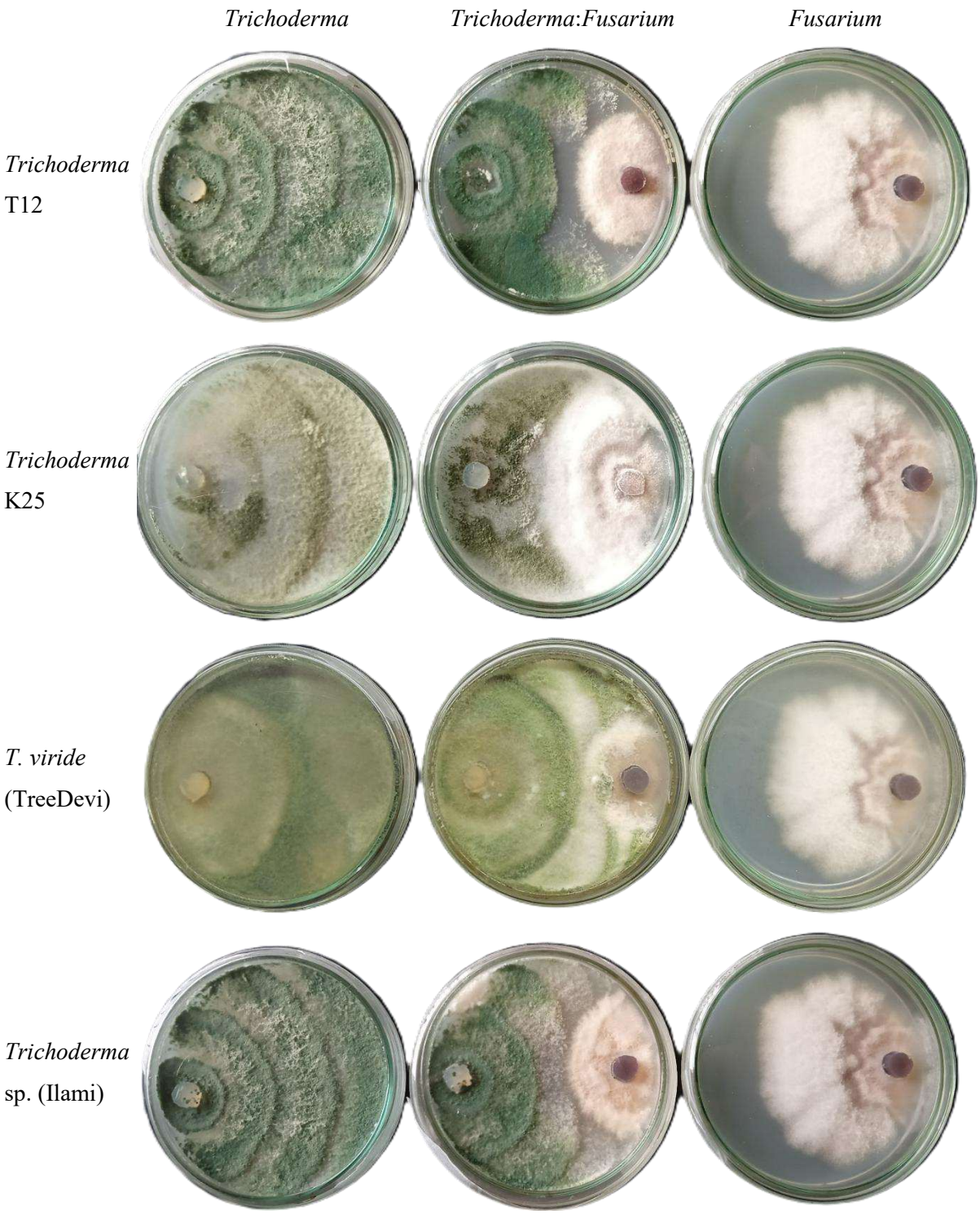


Figure 4 Dual-culture assay showing the antagonistic interaction of four *Trichoderma* isolates against *Fusarium* sp. on PDA.

3.4 Detached fruit assay

3.4.1 Effect on lesion diameter

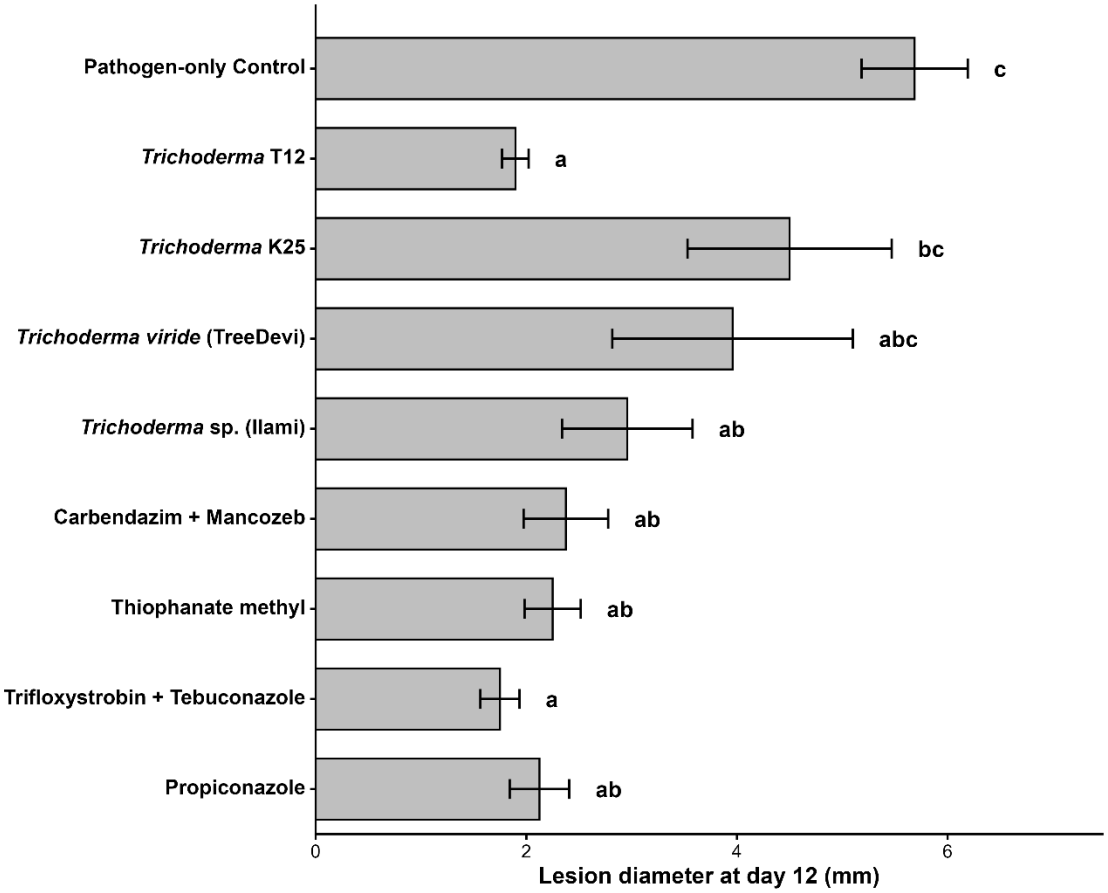


Figure 5 Mean lesion diameter of inoculated fruits treated with various *Trichoderma* and chemical treatments, including water-treated control after 12 days of inoculation. Error bars represent the standard error (SE) of the mean for each treatment. Bold letters next to the error bars indicate statistical groupings based on Tukey's HSD test ($P < 0.05$); treatment bars sharing the same letter are not significantly different from each other.

The size of the symptomatic lesions varied significantly among the treatments (ANOVA, $p<0.001$). The pathogen-inoculated control fruits with no *Trichoderma* or fungicide treatments had the largest lesions (5.69 mm). *Trichoderma* K25 and *Trichoderma viride* (TreeDevi) did not have lesions significantly different than the controls. All other treatments had significantly smaller lesions than the control. Trifloxystrobin + Tebuconazole (1.75 mm) had the smallest lesions of all treatments, which was statistically similar to *Trichoderma* T12 (1.90 mm) (Fig. 5 & 7).

3.4.2 Effect on disease progression

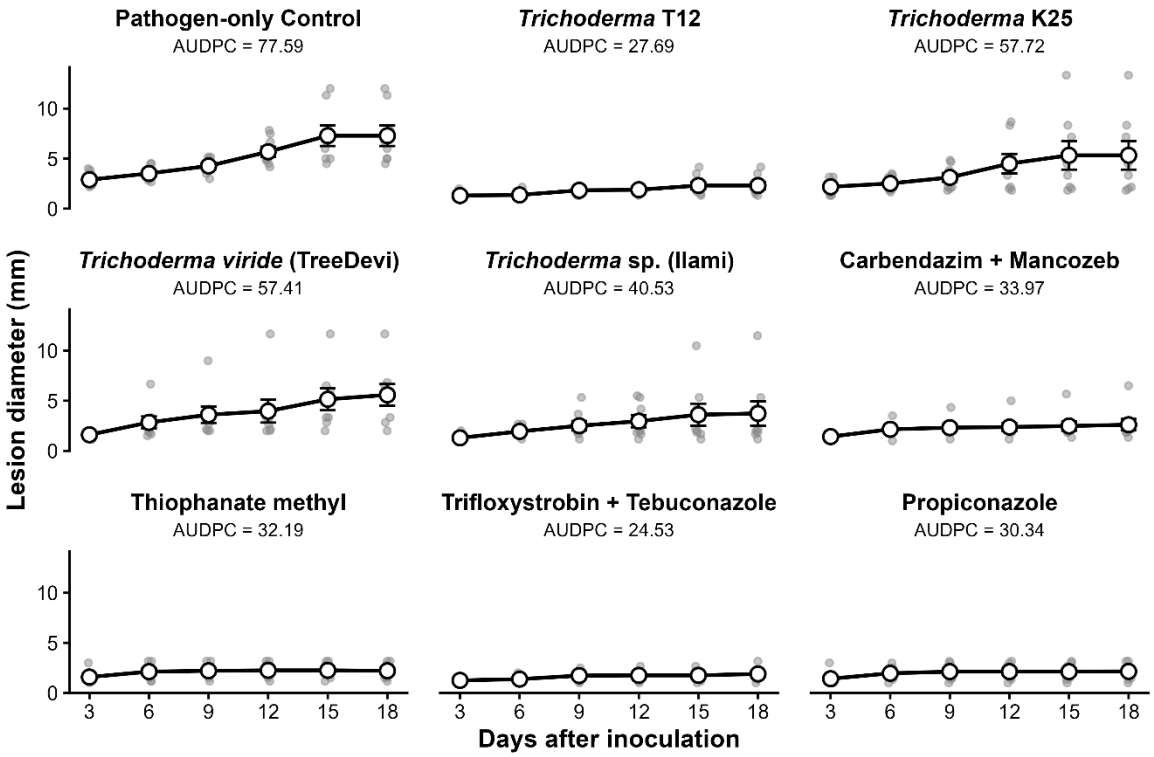


Figure 6 Disease progress curve of *Fusarium* rot on banana fruits treated with different *Trichoderma* and chemical treatments, including water-treated control. The corresponding area under the disease progress curve is indicated within each panel.

Disease progression was reflected by disease progress curves and summarized by AUDPC values (Fig. 6). The pathogen-only control had the highest cumulative disease development (AUDPC = 77.59 mm days). All other evaluated treatments showed lower disease progression. Among the *Trichoderma* treatments, *Trichoderma* T12 (27.69 mm days) had the lowest AUDPC, while the Trifloxystrobin and Tebuconazole combination among the fungicides had the lowest AUDPC (24.53 mm days).



Figure 7. Representative banana fruits from the detached fruit assay showing lesion development caused by *Fusarium* sp. following treatment across different treatments, photographed at 12 days after inoculation. From right: Control, *Trichoderma* T12, *Trichoderma* K25,

T. viride (TreeDevi), *Trichoderma* sp. (Ilami), Carbendazim + Mancozeb, Thiophanate methyl, Trifloxystrobin + Tebuconazole, Propiconazole

3.4.3 Effect on ripening and shelf life

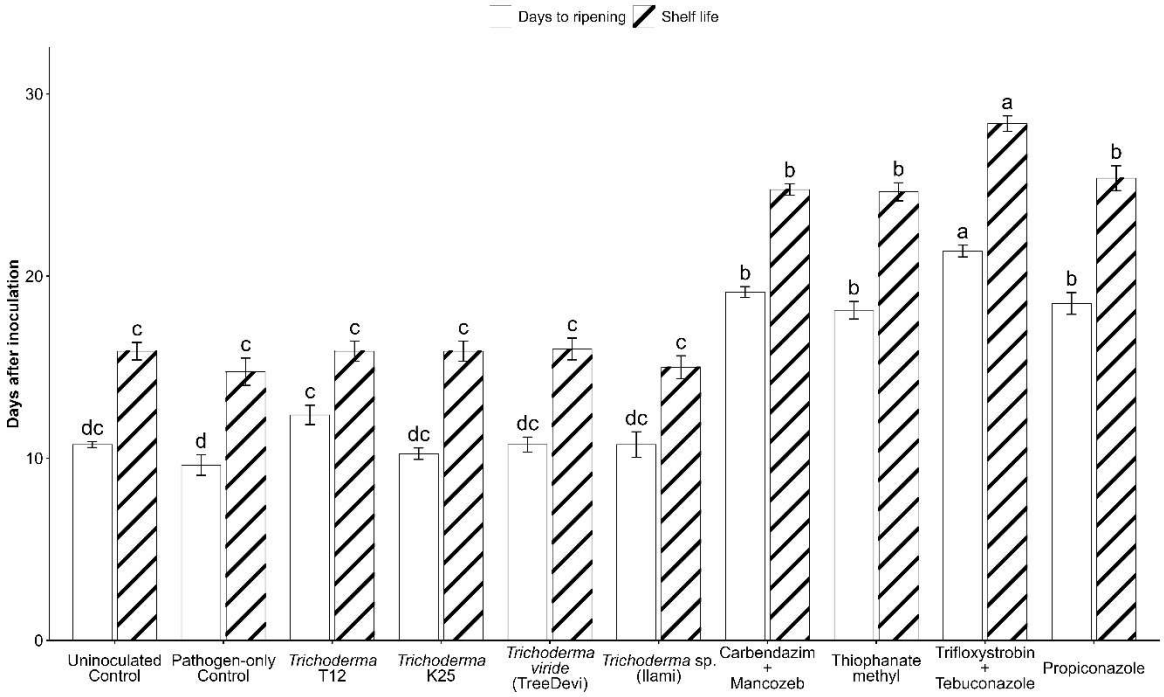


Figure 8 Effect of the *Trichoderma* and chemical treatments on ripening days and shelf life of banana fruits inoculated with *Fusarium* sp. Error bars represent the standard error (SE) of the mean for each treatment. Bold letters above the error bars indicate statistical groupings based on Tukey's HSD test ($P < 0.05$); treatment bars sharing the same letter are not significantly different from each other.

The detached fruit experiments also showed that the evaluated treatments had a significant difference in days to ripening of banana fruits and their shelf life ($P < 0.001$) (Fig. 8). The pathogen-inoculated control fruits were the first to ripen (9.63 days) and rot (14.75 days). The uninoculated control (10.75 and 15.88 days, respectively) was also not significantly different from the pathogen control. Among the *Trichoderma* treatments, *Trichoderma* T12 showed delayed ripening (12.38 days), while others were not significantly different from the controls.

In contrast, all chemical treatments significantly delayed ripening compared to controls and *Trichoderma* treatments. Trifloxystrobin + Tebuconazole took the most days to ripen (21.28 days), followed by Carbendazim + Mancozeb (19.13 days), Propiconazole (18.50 days) and Thiophanate methyl (18.13 days).

The shelf life of the banana fruits also showed similar trends, as *Trichoderma* treatments had no significant effect on shelf life compared to both controls. The chemical fungicides substantially extended the shelf life of the banana fruits, with Trifloxystrobin + Tebuconazole leading with a shelf

life of 28.38 days followed by Propiconazole (25.38 days), Carbendazim + Mancozeb (24.75 days) and Thiophanate methyl (24.63 days).

4 Discussion

In this study, the biocontrol potential of two commercial strains of *Trichoderma* marketed as TreeDevi and Ilami, along with two native *Trichoderma* isolates, was evaluated against a *Fusarium* isolated from symptomatic lesions of post-harvest rots in banana fruits. The efficacy of the isolates was first assessed in vitro using dual culture assays and then under detached fruit assays, adding 4 commonly used fungicides by farmers for comparison. Overall, the results showed that *Trichoderma* isolates were capable of suppressing the *Fusarium*-induced fruit rot in bananas, although the efficacy varied among the treatments.

The isolated pathogen was identified as *Fusarium* sp. and closely resembles the morphological characteristics of *Fusarium sacchari* based on its description in available literature[31,32]. Upon pathogenicity testing, the fungus produced dark brown, necrotic, and sunken lesions and also later formed white mycelial growth on the necrotic lesions under humid conditions, as previously associated with *F. musae*[28].

The dual culture assay showed that all *Trichoderma* isolates inhibited pathogen growth, although the *Trichoderma* K25 isolate showed weak inhibition compared to others. All *Trichoderma* isolates grew towards the direction of the pathogen and quickly overgrew it, except the K25 isolate, which was unable to overgrow the pathogen. But the *Trichoderma* growth was slower in the dual culture plates compared to their respective *Trichoderma*-only controls (data not shown). This shows that the presence of the pathogen may also influence the growth of antagonists. The difference in efficacy among the *Trichoderma* isolates indicates that the antagonistic activity of *Trichoderma* may vary among the isolates even within the same pathosystems, as observed in previous studies[36,37].

When the growth of *Fusarium* sp. in the dual culture plates was compared to that of the radial growth in the pathogen-only control, reduced growth of the pathogen was observed in the dual culture plates even before there was physical contact between the pathogen and the antagonist (data not shown). This early suppression hints at the role of diffusible compounds and biocontrol-related enzymes produced by the *Trichoderma* isolates, as evident from previous studies in *Trichoderma*[36,37].

The *Trichoderma* isolates were further evaluated using detached fruit assays to test whether the in vitro antagonism directly translates to real-world host-associated conditions. This time, four chemical treatments that are commonly used by local banana farmers for preventive fruit treatment were included to compare their efficacy against current management practices. Surprisingly, the relative performance of the *Trichoderma* isolates in this assay was not consistent with the dual culture results, indicating that the antagonism response of an antagonist in an artificial medium may not always translate, as it is, to host-associated conditions[38,39]. T12 was the strongest candidate of

the four, which was in the same statistical grouping as the most effective fungicide of the experiment, Trifloxystrobin + Tebuconazole. Ilami was also statistically similar to other fungicide treatments in terms of lesion diameter. Meanwhile, TreeDevi had an inconsistent response in detached assays despite strong performance in dual culture assays. Previous studies have shown that the greater complexity of host-associated environments can result in differences between the performance of *Trichoderma* observed in vitro and that observed under plant-associated conditions. In vitro assays provide a relatively simplified and controlled environment for evaluating antagonist–pathogen interactions, whereas host-associated systems introduce additional influences related to host colonization, nutrient availability, and host defense responses[40–43]. Furthermore, Sarma et al. (2025) demonstrated that the efficacy of *Trichoderma asperellum* against *Fusarium* wilt of banana can vary between strains and banana cultivars[44]. Although both strains were evaluated against the same pathogen, one strain reduced disease severity, whereas the other showed limited disease suppression in certain cultivar combinations. This strain-dependent variation is consistent with the differences observed between the two commercial *T. viride* treatments in the present study, which also differed in their ability to suppress *Fusarium* rot of banana fruit.

Previous studies have reported conflicting effects of *Trichoderma* on banana ripening and post-harvest longevity. Lima et al. (2025) reported delayed ripening and fruit firmness maintained for an extended period by post-harvest coating of banana fruits using *T. harzianum*[45], and Thangavelu et al. (2024) found suppressed post-harvest diseases and extended shelf life using *T. asperellum* prr2 isolate[27]. However, contrasting responses have been reported by Viencz et al. (2023), where *T. harzianum* seemed to have accelerated the maturation process[46]. Our study adds to this conflicting pool, as we observed no significant influence of *Trichoderma* treatments on shelf life compared to both pathogen-inoculated and uninoculated controls, although T12 showed delayed ripening over the pathogen-inoculated control but no significant shelf-life extension. However, all fungicides significantly delayed ripening and extended the shelf life of the bananas.

Although *Trichoderma* did not significantly improve ripening and shelf life of banana fruits, two of them showed a disease-suppressive capability that was comparable to the chemical fungicides. Especially the T12 isolate, which showed consistent potential under both assays, comes out to be a promising candidate for further evaluation. Although chemical fungicides have significantly extended shelf life, in production systems where organic or low chemical input is a priority, a *Trichoderma* isolate with high disease suppression, for example T12, could be a safer alternative to potentially harmful chemical fungicides. Further optimization of strain selection, formulation, application method and storage conditions will be necessary to determine their suitability for such production systems.

However, there are some factors which can limit the applicability of these findings. First of all, the *Fusarium* and *Trichoderma* isolates were identified based on morphological characteristics and

therefore require molecular confirmation for accurate species-level identification. Moreover, only a single isolate of *Fusarium* was evaluated so the responses may not be generalized among the *Fusarium* population associated with banana fruit rot. The detached fruit assay was conducted under a controlled environment, so it may not fully represent the conditions of commercial storage and transportation. Furthermore, the suggested mechanisms were based on the established literature as the underlying antagonistic activity of *Trichoderma* was not directly assessed. Therefore, future studies should include molecular characterization of the pathogen and antagonists, evaluation at the population level, and validation under real-world conditions. Investigating antagonistic mechanisms of *Trichoderma,* such as diffusible metabolites, volatile compounds, and host response, could help further clarify the differences in efficacy observed among the isolates.

Overall, this study demonstrated the potential of *Trichoderma* as a biological approach for post-harvest *Fusarium* rot of banana. We found that the native *Trichoderma* T12 isolate had strong performance across both in vitro and detached fruit assays, making it a particularly promising candidate for further studies. Although chemical fungicides provided greater benefits in terms of ripening and shelf life, potent *Trichoderma* isolates may offer a useful alternative in organic and low chemical production systems. Further validation under practical postharvest conditions will be essential before wider application.

Data Availability Statement

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Hemant Joshi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing; **Gokul Dev Bhatta:** Investigation; **Surekha Pandeya:** Investigation, Writing – original draft; **Kabi Raj Bhatt:** Investigation, Data curation; **Jhalak Bahadur Mauni:** Investigation; **Dichhya Bhatt:** Investigation; **Ashish Ghimire:** Writing – review & editing

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