

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(8): 2503-2509
www.biochemjournal.com
Received: 01-06-2026
Accepted: 04-07-2026

Mummineni Sunitha
Ph.D. Scholar, Department of
Plant Pathology, College of
Agriculture V. C. Farm, University
of Agricultural Sciences, Mandya,
Karnataka, India

Pankaja NS
Professor and Head, Department of
Plant Pathology, College of
Agriculture V. C. Farm, University
of Agricultural Sciences, Mandya,
Karnataka, India

Umashankar Kumar N
Professor and Senior Farm
Superintendent, Organic Farming
Research Station, Naganahalli,
Mysore, Karnataka, India

Kiran Kumar N
Professor, Department of Plant
Pathology, College of Agriculture
V. C. Farm, University of
Agricultural Sciences, Mandya,
Karnataka, India

Mahadeva J
Assistant Professor, Department of
Forestry and Environmental
sciences, College of Agriculture V.
C. Farm, University of Agricultural
Sciences, Mandya, Karnataka,
India

B Divya
Scientist, Department of
Horticulture, ICAR, Krishi Vigyan
Kendra (KVK), V. C. Farm,
University of Agricultural Sciences,
Mandya, Karnataka, India

Suma R
Professor, Department of Soil
Science and Agricultural
Chemistry, College of Agriculture,
V. C. Farm, University of
Agricultural Sciences, Mandya,
Karnataka, India

Corresponding Author:
Mummineni Sunitha
Ph.D. Scholar, Department of
Plant Pathology, College of
Agriculture V. C. Farm, University
of Agricultural Sciences, Mandya,
Karnataka, India

Identification of resistant sources in chilli hybrids and evaluation of copper-chitosan nanocomposites against *Colletotrichum truncatum*

Mummineni Sunitha, Pankaja NS, Umashankar Kumar N, Kiran Kumar N, Mahadeva J, B Divya and Suma R

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8Sab.9779>

Abstract

Chilli anthracnose caused by *Colletotrichum truncatum* is an important constraint to chilli (*Capsicum annuum* L.) production and causes significant yield and post-harvest losses. The present study was conducted to evaluate the resistance of *C. truncatum* in six chilli hybrids and to evaluate the antifungal efficacy of copper-chitosan nanocomposites (CuChNCs). Disease severity was quantified using Percent disease index (PDI) and resistant screening was done using greenhouse and detached fruit assays. Among the chilli hybrids tested, Arka Tejasvi, Arka Swetha and Arka Harita were highly susceptible, whereas Arka Meghana showed moderate resistance. The results showed that CuChNCs had superior antifungal activity compared to conventional treatments, such as copper oxychloride and chitosan alone. Complete inhibition of disease was observed at 500 ppm CuChNCs, whereas lower concentrations also significantly reduced lesion development and disease severity. In contrast, copper oxychloride and chitosan alone were less effective. The increased efficacy of CuChNCs may be attributed to their synergistic antimicrobial properties, improved interaction with fungal cells and sustained release of active components. The experiment highlights the significance of copper-chitosan nanocomposites as an effective and environmentally-friendly method for the management of chilli anthracnose and provides a basis for developing sustainable disease management strategies.

Keywords: Antifungal activity, *Capsicum annuum*, copper-chitosan nanocomposites, disease management, nanofungicides, susceptibility

1. Introduction

Chilli (*Capsicum annuum* L.) is one of the most important spice and vegetable crops cultivated all over the world, valued for its culinary, nutritional and economic significance. It is a rich source of vitamins A and C, capsaicin and antioxidants and also plays a vital role in the food processing and pharmaceutical industries (Rajendran and Thomas, 2021) [15]. India is one of the largest producer and exporter of chilli but its productivity is significantly constrained by various biotic stresses, particularly fungal diseases. Among the major diseases affecting chilli, anthracnose caused by several species of the genus *Colletotrichum* is considered one of the most destructive, causing severe losses in both yield and fruit quality under field and post-harvest conditions (Pakdeevaporn *et al.*, 2005) [13]. The disease affects leaves, stems and especially fruits, where it produces sunken necrotic lesions that reduce marketability and shelf life. In addition, anthracnose has been found to cause yield losses of more than 50% in Thailand under favorable environmental conditions especially in humid and warm environment (Pakdeevaporn *et al.*, 2005) [13] and in India, disease incidence levels varied from 66 to 84% and yield losses ranged from 12 to 50% (Thind and Jhooty, 1985, Bagri *et al.*, 2004, Sharma *et al.*, 2005) [23, 1, 18].

Anthracnose of chilli is caused by a complex of *Colletotrichum* species, including *C. capsici*, *C. gloeosporioides* and *C. truncatum*. Among these, *C. truncatum* is highly aggressive and widespread, resulting in severe fruit rot and rapid disease progression (Damm *et al.*, 2012; Cannon *et al.*, 2012) [5, 3]. The pathogen colonise host tissues at different growth stages, but fruit infection is of major economic importance. Disease development is influenced by environmental factors such as temperature, humidity and host ontogeny. Ripe fruits tend to be more vulnerable compared to fruits that are not yet matured.

Disease control of chilli anthracnose largely depends on the use of chemical fungicides such as copper oxychloride, carbendazim and mancozeb. Eventhough they are effective in controlling the disease, excessive and indiscriminate use of these chemicals has led to several concerns, including the development of resistance to fungicides in pathogen populations, environmental contamination and accumulation of toxic residues in food products (Lucas *et al.*, 2015) [9]. These constraints underscore the urgent need to develop sustainable and environment-friendly disease management strategies.

Nanotechnology has recently proved to be an efficient tool for controlling plant pathogens because it is capable of increasing efficiency in a way that would reduce the negative impact of chemicals on the environment. Chitosan, being a biopolymer formed from chitin, is a substance that has been extensively studied lately owing to its biodegradability, biocompatibility and inherent antifungal properties. It also acts as an elicitor of plant defense mechanisms, inducing the production of phytoalexins and pathogenesis-related proteins (El Hadrami *et al.*, 2010; Pichyangkura and Chadchawan, 2015) [6, 14]. The incorporation of metal ions such as copper into chitosan matrices leads to the formation of copper-chitosan nanocomposites, which exhibit enhanced antimicrobial activity. These nanocomposites possess unique properties such as increased surface area, improved adhesion to plant surfaces, controlled release of active ions and better penetration into microbial cells. Copper ions are proven to affect the fungal cellular structure by disrupting their cell walls, denaturing proteins and causing enzymatic activities, thus inhibiting the pathogen growth (Lemire *et al.*, 2013; Salah *et al.*, 2021) [8, 16]. The synergistic interaction between copper and chitosan further enhances their antifungal efficacy.

Although the nanocomposite material of copper-chitosan shows considerable promise, the number of investigations related to the efficacy of copper-chitosan nanocomposites against *Colletotrichum truncatum* in chili pepper is limited. In addition, variability in host resistance among different chilli hybrids plays a crucial role in disease development and management. Identification of resistant or moderately resistant hybrids, combined with effective nanocomposite-based treatments, can contribute significantly to integrated disease management strategies. Hence, the experiment was planned to investigate the following objectives (i) evaluate the resistance of selected chilli hybrids to anthracnose caused by *Colletotrichum truncatum* and (ii) assess the antifungal efficacy of copper-chitosan nanocomposites under controlled conditions. The findings of this study are expected to provide insights into sustainable and environmentally safe approaches for managing chilli anthracnose.

2. Materials and Methods

2.1 Experimental Location

The study was conducted under greenhouse and laboratory conditions in the Department of Plant Pathology during *khari* 2025. Laboratory experiments involving pathogen isolation, culturing and inoculum preparation were conducted in a sterile environment under aseptic conditions. Greenhouse experiment was maintained favourable for the development of chilli anthracnose disease.

2.2 Plant Material

Six chilli hybrids were selected: Arka Tejasvi, Arka Gagan, Arka Kyathi, Arka Swetha, Arka Meghana, Arka Harita for evaluating their susceptibility to anthracnose disease caused by *Colletotrichum truncatum*.

2.3 Pathogen Isolation and Inoculum Preparation

The pathogen *Colletotrichum truncatum* was cultured on suitable media. A conidial suspension (1×10^6 cfu mL⁻¹) was prepared from 12 day old cultures. For inoculum preparation, sterile distilled water was added to fully grown fungal cultures and the colony surface was gently scraped using a sterile glass rod to release conidia. The resulting suspension was filtered through double-layered muslin cloth to remove mycelial debris. The concentration of conidia was adjusted to 1×10^6 cfu mL⁻¹ using a haemocytometer. The prepared conidial suspension was used immediately for pathogenicity tests and antifungal evaluation studies.

2.4 Resistance Assessment of Chilli Hybrids to Anthracnose Disease

Six different chilli hybrids - Arka Tejasvi, Arka gagan, Arka kyathi, Arka Swetha, Arka Meghana and Arka Harita were used for testing the susceptibility of chilli anthracnose pathogen. Plastic bags (15x12 cm) were filled with sterilized soil-sand-FYM (farm yard manure) mix (2:1:1) and autoclaved at 15 psi for two hours for three consecutive days. Simultaneously, the bags were also sterilized with 4 percent formalin solution to eliminate the residual contaminants. Each bag was transplanted with one seedling of six different chilli hybrids. The bags were placed in a greenhouse with five replications. Fertilizers and water applied as per the need to maintain optimum moisture for growth of seedlings in the greenhouse.

The conidial suspension (10^6 cfu/ml) was prepared by scraping the 12 days old culture plate of *Colletotrichum truncatum*. The Red ripe and green fruits of different chilli hybrids was collected. The collected fruits are surface sterilized with 1 per cent sodium hypochlorite and followed by twice washing with distilled water. Then the fruits are placed in a Petri plate containing the moist blotter paper to maintain the humidity and conidial suspension was inoculated by pin pricking method (Manzoor *et al.*, 2023) [11]. After inoculation the Petri plates were incubated at 27 ± 2 °C in BOD incubator and monitored for symptom development; re-isolation was made from the infected fruits and compared with the original to prove Koch's postulates. Observation was taken for no. of lesions, lesion length, lesion width and PDI were calculated to know the susceptible variety of chilli for further evaluation.

2.5 Disease Assessment

Table 1: Disease rating scale of Chilli Anthracnose (0-9 Scale) was used to assess the disease severity as described by Mayee and Datar (1986) (Plate 1):

Scale	Description
0	No symptoms on the leaf or branch or fruit
1	1-10% or less infection of leaf or branch or fruit
3	11-25% infection on the leaf or branch or fruit
5	26-50% infection of leaf or branch or fruit
7	51-75% infection of leaf or branch or fruit
9	75% and above infection area of leaf or branch or fruit

Further, the scale was converted to per cent disease index (PDI) using the formula by Wheeler (1969) [24]:

$$\text{Percent Disease Index (PDI)} = \frac{\text{Sum of individual ratings}}{\text{Total number of plants/Leaves observed}} \times \frac{100}{\text{Maximum disease grade}}$$

Percent disease intensity (PD Intensity) was further calculated based on infection levels by using the disease rating scale (Machenahalli *et al.*, 2016) [17] as follows:

Table 2: Disease Reaction Scale for Assessment of Resistance in Chilli Hybrids against Anthracnose Disease

Grade	Branches infected per plant	Reaction
0	0	Immune
1	1-10	Resistant
3	11-25	Moderately resistant
5	26-50	Moderately susceptible
7	51-75	Susceptible
9	>75	Highly susceptible

2.6 Symptomatology of Chilli Anthracnose Caused by *Colletotrichum truncatum*

Anthracnose symptoms caused by *Colletotrichum truncatum* were observed on different plant parts of chilli under both greenhouse and laboratory conditions. The disease progression was found to vary depending on the stage of the host tissue and environmental conditions.

2.7 Evaluation of Copper chitosan nanocomposites on detached unripe chilli fruits

The experiment was carried out on detached chilli fruits under controlled laboratory conditions. The best treatments under *in-vitro* evaluation (poison food technique) were evaluated on detached fruits. Fruits from susceptible chilli cultivar Arka Tejasvi were evaluated under controlled conditions. Fruits were surface sterilized with 1 percent Sodium hypochlorite solution for 30 seconds and washed thoroughly with sterile distilled water. The surface sterilized fruits were dried by placing on sterilized blotter paper. Different treatments were applied on test fruits after 48 hrs of spore (*C. truncatum*) inoculation. All the fruits were given pin-pricks at three specific points and then spray inoculated with spore suspension (10^6 spores/ml) of seven days old culture of *C. truncatum*. The treated fruits were kept in moist chamber and incubated at $28 \pm 2^\circ\text{C}$ for 5 days. The fungicide served as standard check while as sterilized distilled water (SDW) was applied in case of control. Three replications of each treatment were maintained and observations taken under completely randomized design. Observations on number of lesions and size (length) of lesions were recorded on 5th day after inoculation.

3. Results and Discussion

3.1 Pathogenicity and Resistance screening of Chilli Hybrids against *Colletotrichum truncatum*

The pathogenicity of *C. truncatum* was successfully confirmed through detached fruit inoculation assays and greenhouse pathogenicity tests. Typical anthracnose symptoms developed consistently across all inoculated chilli hybrids under both experimental conditions. The first primary symptoms observed as small, water-soaked lesions at the site of inoculation, which gradually enlarged into

sunken necrotic spots with dark brown discoloration. Under humid conditions, the presence of characteristic acervuli with salmon-pink spore masses were observed on infected fruits, confirming the typical symptomatology of chilli anthracnose caused by *C. truncatum*.

The development of disease was showed greater effects in case of matured red ripe fruits compared to green fruits, thus indicating the influence of fruit maturity on host susceptibility. The re-isolations of fungus from artificially infected fruits resulted in colonies of fungi that showed morphological resemblance with the initial isolation, thereby fulfilling Koch's postulates for the causal organism and confirming *C. truncatum* as the causal agent of anthracnose in chilli.

3.1.2 Assessment of Disease Reaction in Chilli Hybrids against Anthracnose

Considerable variation in resistance to chilli anthracnose was observed among the evaluated chilli hybrids under detached fruit and greenhouse conditions. The differential disease response indicated the presence of genetic variability among hybrids with respect to resistance against *C. truncatum* infection. Based on Percent Disease Index (PDI), the hybrids were categorized as follows: Highly susceptible were Arka Tejasvi, Arka Swetha, Arka Harita; Susceptible were Arka Gagan; moderately susceptible were Arka Kyathi; moderately resistant were Arka Meghana.

From the hybrids tested, Arka Tejasvi was found to have the highest disease severity with values of PDI going up to 100 percent in both greenhouse condition and in detached red fruit conditions, implying high susceptibility to the anthracnose pathogen infection (Plate 3 and Plate 2). This hybrid exhibited rapid lesion expansion, extensive tissue necrosis and profuse sporulation of the pathogen. Similarly, Arka Swetha and Arka Harita also showed severe disease symptoms with high lesion development and elevated PDI values. On the other hand, Arka Meghana exhibited the lowest disease severity with comparatively smaller lesions and reduced pathogen colonization, suggesting the presence of partial resistance mechanisms against *C. truncatum* as mentioned in Table 3, Plate 2. The lower susceptibility observed in Arka Meghana may be attributed due to inherent structural and biochemical defense responses that restrict fungal establishment and disease progression. Therefore, this hybrid may serve as a potential genetic source in future resistance breeding programs aimed at developing anthracnose-resistant chilli cultivars. Furthermore, disease severity was consistently higher in detached red fruits compared to green fruits across all hybrids, indicating that fruit maturity plays a significant role in the development and progression of anthracnose disease in chilli.

3.2 Symptomology difference between different hybrids

Some of the easily distinguishable and economically significant symptoms of anthracnose on chilli fruit caused by *C. truncatum* were observed on fruits, in case of

susceptible hybrids initial infection appeared as small, circular, water-soaked lesions, particularly at the site of inoculation. These lesions progressively enlarged, becoming sunken, necrotic spots with dark brown to black discoloration and eventually coalesced to form large depressed areas that markedly reduced fruit quality. Under high humid conditions, characteristic concentric rings of acervuli developed within the lesions, appearing as black pinhead-like structures that produced salmon-pink spore masses, a diagnostic feature of *Colletotrichum* infection. Similar observations were reported by Damm *et al.* (2012)^[5], who described *C. truncatum* as a highly aggressive species associated with severe anthracnose symptoms in chilli and other *solanaceous* hosts. In advanced stages, infected fruits exhibited severe shrivelling, rotting and premature abscission, resulting in substantial yield losses (Plate 3). The moderately resistant chilli hybrids exhibited small, white necrotic restricted lesions at the infection site, suggesting localized cell death and no further colonization was evident for *C. truncatum*.

However, the manifestation of symptoms depended on the maturity status of the fruits, such that green fruits showed slower disease development with smaller lesions and delayed sporulation, whereas ripe (red) fruits were highly susceptible to the pathogen, expressing rapid lesion expansion, profuse sporulation and increased disease severity, indicating the critical role of physiological maturity in host susceptibility. Although infection was predominantly fruit-based, mild symptoms were also observed on vegetative parts, where leaves developed small, irregular necrotic spots surrounded by chlorotic halos that could enlarge under severe infection, leading to blighting and premature senescence. Similar observations were reported by Than *et al.* (2008)^[22] and Temiyakul *et al.* (2012)^[21], who observed enhanced lesion development and faster disease progression in mature chilli fruits infected by *Colletotrichum* spp. In detached fruit assays, symptom development was evident within 3-5 days after inoculation, particularly at pin-pricked sites, confirming wounds as major entry points for the pathogen; lesion number and size increased progressively in positive control, whereas fruits treated with copper-chitosan nanocomposites exhibited delayed symptom onset and reduced lesion development, demonstrating effective disease suppression.

3.3 Efficacy of Copper Chitosan Nanocomposites against *Colletotrichum truncatum*

CuChNCs exhibited significant antifungal activity against *C. truncatum* under detached fruit conditions and effectively suppressed anthracnose symptom development in green chilli. The nanocomposites demonstrated a clear dose-dependent response, wherein increasing concentrations

resulted in progressive reduction of lesion development and disease severity.

Among the different concentrations tested, CuChNCs at 500 ppm completely inhibited disease development, recording zero Percent Disease Index (PDI), indicating absolute suppression of pathogen infection and lesion formation. Similarly, treatments with 300 ppm and 200 ppm CuChNCs significantly reduced disease severity, recording only 3.70% and 7.41% PDI, respectively. The treated fruits exhibited reduced lesion number, smaller lesion size and delayed symptom expression compared to untreated control fruits (Table 4 and Plate 4). Similar synergistic effects of copper-chitosan nanocomposites against phytopathogens have been reported by recent studies on *Fusarium* species (Mosa and El-Abeid, 2023; Tarakanov *et al.*, 2023)^[12, 20].

Conventional treatments such as copper sulphate (CuSO₄), COC and chitosan applied individually were comparatively less effective in suppressing anthracnose disease. Copper sulphate treatments recorded high disease severity with PDI values reaching up to 92.59%, while chitosan alone showed moderate disease reduction with maximum PDI of 77.78%. The untreated positive control fruits exhibited severe symptom development with 100% PDI, characterized by extensive tissue necrosis, sunken lesions and profuse sporulation of the pathogen (Plate 4). In contrast, nanocomposite-based formulations provide improved efficacy at lower dosages while minimizing environmental contamination and excessive copper usage. Recent studies have emphasized the potential of chitosan-based nanocomposites as sustainable alternatives to conventional fungicides in integrated disease management programs (Chiquito-Contreras *et al.*, 2026; Hashim *et al.*, 2024)^[4, 7].

The enhanced antifungal efficacy of CuChNCs against *C. truncatum* may be attributed due to the synergistic interaction between copper ions and chitosan polymer matrix. The nanoscale formulation likely improved the surface area and interaction of the active compounds with fungal cells, resulting in disruption of membrane integrity, leakage of intracellular contents and inhibition of fungal growth. In addition, the sustained release of copper ions from the chitosan matrix may have contributed to prolonged antifungal activity and effective suppression of pathogen colonization. These effects have also been observed in other recent nanofungicide studies by Shoala *et al.* (2025)^[19] and Malook *et al.* (2026)^[10], who reported enhanced pathogen suppression through controlled ion release and reactive oxygen species (ROS)-mediated cellular damage. The findings clearly demonstrate the superior antifungal potential of CuChNCs over conventional treatments and highlight their promise as eco-friendly nanofungicides for sustainable management of chilli anthracnose caused by *C. truncatum*.

Table 3: Comparative resistance of different chilli hybrids against *Colletotrichum truncatum* under detached green fruit, detached red fruit and greenhouse conditions

S. No.	Hybrids Arka	Green detached fruits				Red detached fruits				Greenhouse			
		No. of Lesions	Lesion length (cm)	Lesion width (cm)	PDI	No. of Lesions	Lesion length (cm)	Lesion width (cm)	PDI	No. of Lesions	Lesion length (cm)	Lesion width (cm)	PDI
1	Tejasvi	1	5.16	0.7	77.78 (61.88)	3	6	0.6	100.00 (90.00)	3	6.1	0.7	100.00 (90.00)
2	Gagan	2	0.6	0.3	44.44 (41.81)	2	0.83	0.25	70.37 (57.02)	3	1.24	0.3	70.37 (57.02)
3	Kyathi	1	1.27	0.3	33.33 (35.26)	2	3.17	0.5	33.33 (35.26)	3	3.34	0.5	55.56 (48.19)
4	Swetha	1	2.83	0.5	62.96 (52.51)	3	4.1	0.75	85.19 (67.37)	3	4.36	0.9	85.19 (67.37)
5	Meghana	1	0.2	0.1	14.81 (22.63)	1	0.3	0.1	11.11 (19.47)	2	0.34	0.1	29.63 (32.98)
6	Haritha	1	2.27	0.3	55.56 (48.19)	2	3.33	0.3	77.78 (61.88)	3	3.5	0.3	77.78 (61.88)

Figures in parentheses indicate arc sine transformed values.

Table 4: To assess the anti-fungal activity of Copper chitosan nanocomposites against anthracnose of chilli by detached green fruit method:

Treatments	No. of Lesions	Lesion length	Lesion width	PDI (5 DAT)
Chi 200 ppm	8	2.4	1.2	77.78 (61.88)
Chi 300 ppm	6	2.0	1	62.96 (52.51)
Chi 500 ppm	5	1.8	0.9	55.56 (48.19)
CuSO ₄ 200 ppm	8	2.6	1.3	92.59 (74.21)
CuSO ₄ 300 ppm	7	2.5	1.2	85.19 (67.37)
CuSO ₄ 500 ppm	6	2.4	1.3	77.78 (61.88)
CNP 200 ppm	4	1.6	0.7	40.74 (39.62)
CNP 300 ppm	3	1.4	0.5	33.33 (35.26)
CNP 500 ppm	2	1.2	0.4	25.93 (30.61)
CuChNC 50 ppm	3	1.1	0.4	22.22 (28.13)
CuChNC 100 ppm	2	0.8	0.2	14.81 (22.63)
CuChNC 200 ppm	2	0.6	0.2	7.41 (15.79)
CuChNC 300 ppm	1	0.2	0.1	3.70 (11.10)
CuChNC 500 ppm	0	0.0	0	0.00 (0.00)
COC @ 2.5 g/L	5	1.2	0.4	14.81 (22.63)
Positive Control	9	2.5	1.4	100.00 (90.00)

Figures in parentheses indicate arc sine transformed values.

**Plate 1:** Disease rating scale (0-9) used for assessment of chilli anthracnose severity caused by *Colletotrichum truncatum* on chilli fruits

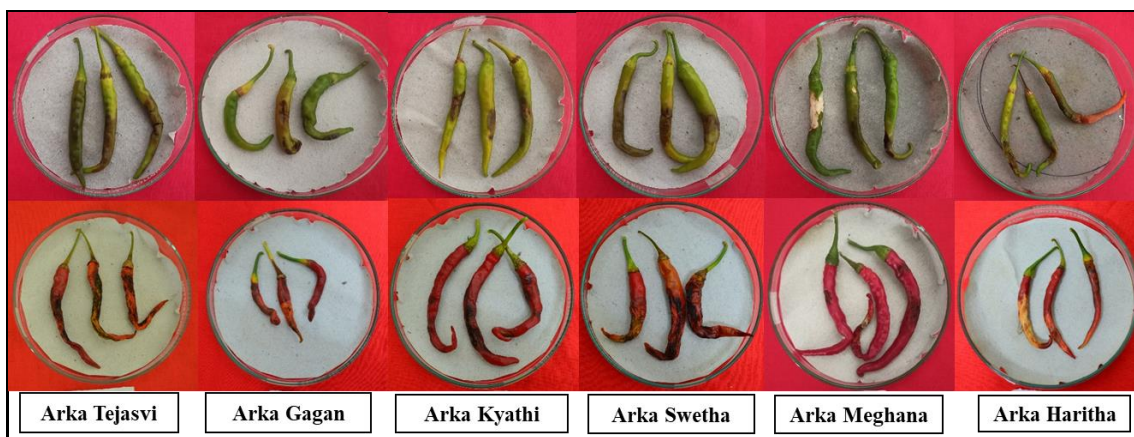


Plate 2: Resistance of *Colletotrichum truncatum* on detached green and red chilli fruits of different hybrids using the detached fruit inoculation method.



Plate 3: Resistance of *Colletotrichum truncatum* of different hybrids under greenhouse conditions

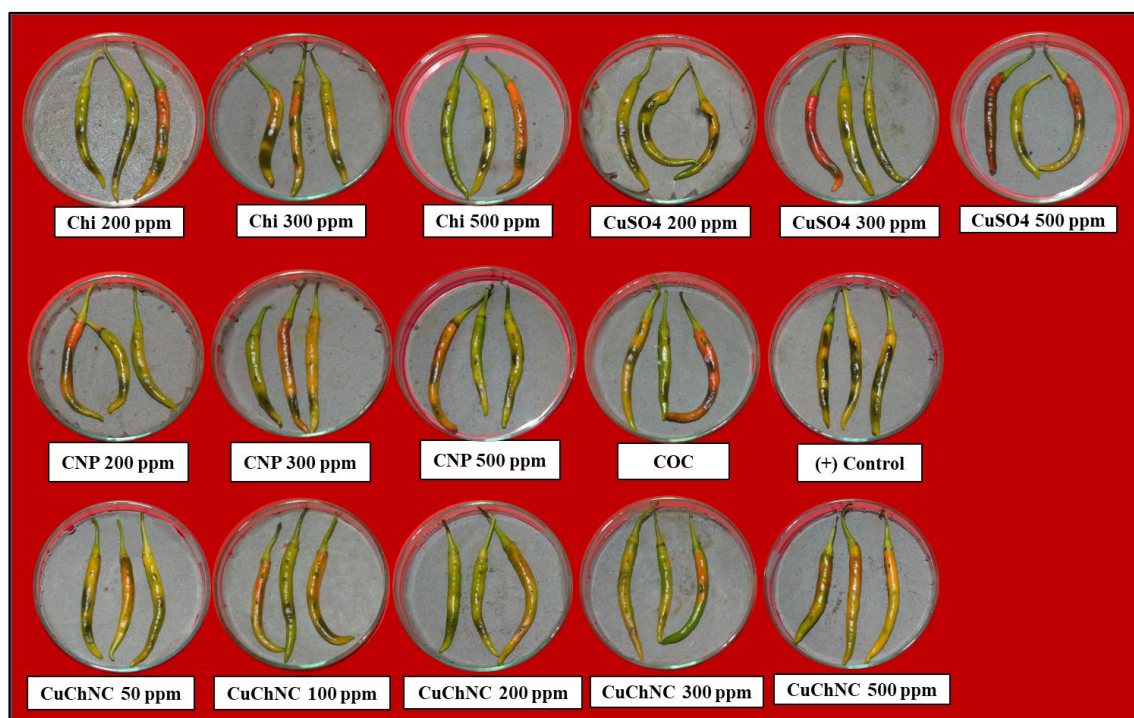


Plate 4: Antifungal efficacy of different treatments against *Colletotrichum truncatum* causing chilli anthracnose under detached fruit assay conditions

4. Conclusion

The study demonstrates that *C. truncatum* is highly pathogenic to chilli, with significant variability among hybrids. Copper-chitosan nanocomposites showed exceptional antifungal efficacy, achieving complete disease suppression at higher concentrations. These findings suggest that CuChNCs are a promising eco-friendly alternative to conventional fungicides and hold significant potential for integrated disease management strategies in chilli cultivation.

Conflict of Interest

The authors declare no competing interests

Acknowledgement

The authors are grateful to Department of Plant Pathology, Department of Forestry and Environmental sciences, Soil Science and Agricultural Chemistry, College of Agriculture, V.C. Farm, Mandya, Organic Farming Research Station, Naganahalli, Department of Horticulture, ICAR, Krishi Vigyan Kendra (KVK), V. C. Farm, Mandya for the financial support and for providing laboratory facilities to conduct the research.

5. References

1. Bagri RK, Choudhary SL, Rai PK. Management of fruit rot of chilli with different plant products. *Annals of Plant Protection Sciences*. 2004;12:107-109.
2. Brent KJ, Hollomon DW. Fungicide resistance: the assessment of risk. Vol. 2. Brussels, Belgium: Global Crop Protection Federation; 1998.
3. Cannon PF, Damm U, Johnston PR, Weir BS. *Colletotrichum*: current status and future directions. *Studies in Mycology*. 2012;73(1):181-213.
4. Chiquito-Contreras RG, Herrera-Feijoo RJ, Reyes-Pérez JJ, Ramírez-Machado C, Hernández-Adame L, Torres-Rodríguez JA, et al. Integrated control of tomato damping-off using *Stenotrophomonas rhizophila* and CuO nanoparticles. *Crops*. 2026;6(2):48.
5. Damm U, Cannon PF, Woudenberg JHC, Crous PW. The *Colletotrichum acutatum* species complex. *Studies in Mycology*. 2012;73:37-113.
6. El Hadrami A, Adam LR, El Hadrami I, Daayf F. Chitosan in plant protection. *Marine Drugs*. 2010;8(4):968-987.
7. Hashim AF, Youssef K, Ahmed FK, Alghuthaymi MA. Chitosan-based agronano-fungicides: a sustainable alternative in fungal plant diseases management. In: *Nanohybrid Fungicides*. Elsevier; 2024. p. 45-70.
8. Lemire JA, Harrison JJ, Turner RJ. Antimicrobial activity of metals: mechanisms, molecular targets and applications. *Nature Reviews Microbiology*. 2013;11:371-384.
9. Lucas JA, Hawkins NJ, Fraaije BA. The evolution of fungicide resistance. *Advances in Applied Microbiology*. 2015;90:29-92.
10. Malook MB, Ijaz M, Ijaz R, Shang J, Lv L, Ahmed T, et al. Nanotechnology-based strategies for sustainable management of bacterial plant diseases: mechanisms, applications and future directions. *Environmental Science: Nano*. 2026;13(2):723-747.
11. Manzoor MA, Shah IH, Ali Sabir I, Ahmad A, Albasher G, Dar AA, et al. Environmental sustainable: biogenic copper oxide nanoparticles as nano-pesticides for investigating bioactivities against phytopathogens. *Environmental Research*. 2023;231:115941.
12. Mosa MA, El-Abeid SE. Chitosan-loaded copper oxide nanoparticles: a promising antifungal nanocomposite against fusarium wilt disease of tomato plants. *Sustainability*. 2023;15(19):14295.
13. Pakdeevraporn P, Wasee S, Taylor PWJ, Mongkolporn O. Inheritance of resistance to anthracnose caused by *Colletotrichum capsici* in *Capsicum*. *Plant Breeding*. 2005;124:206-208.
14. Pichyangkura R, Chadchawan S. Biostimulant activity of chitosan in horticulture. *Scientia Horticulturae*. 2015;196:49-65.
15. Rajendran S, Thomas G. Economic importance and global trends in chilli production. *Indian Journal of Agricultural Economics*. 2021;76(2):198-210.
16. Salah I, Parkin IP, Allan E. Copper as an antimicrobial agent: recent advances. *RSC Advances*. 2021;11:18179-18186.
17. Machenahalli S, Nargund VB, Byadgi AS, Hegde Y. Integrated management of die-back and fruit rot of chilli (*Capsicum annum* L.). *Vegetos*. 2016;29:3.
18. Sharma PN, Kaur M, Sharma OP, Sharma P, Pathania A. Morphological, pathological and molecular variability in *Colletotrichum capsici*, the cause of fruit rot of chillies in the subtropical region of north-western India. *Journal of Phytopathology*. 2005;153(4):232-237.
19. Shoala T, El-Garhy HA, Messiha NA, El-Abeid SE. The efficacy of nanoparticles on soil microbial biodiversity and the prevention of *Fusarium* wilt disease (*Fusarium oxysporum* f. sp. *lycopersici*). *BMC Microbiology*. 2025;25(1):305.
20. Tarakanov R, Shagdarova B, Lyalina T, Zhuikova Y, Il'ina A, Dzhililov F, et al. Protective properties of copper-loaded chitosan nanoparticles against soybean pathogens *Pseudomonas savastanoi* pv. *glycinea* and *Curtobacterium flaccumfaciens* pv. *flaccumfaciens*. *Polymers*. 2023;15:1100.
21. Temiyakul P, Taylor PW, Mongkolporn O. Differential fruit maturity plays an important role in chili anthracnose infection. *Journal of King Mongkut's University of Technology North Bangkok*. 2012;22(3):494-504.
22. Than PP, Jeewon R, Hyde KD, Pongsupasamit S, Mongkolporn O, Taylor PWJ. Characterization and pathogenicity of *Colletotrichum* species associated with anthracnose on chilli (*Capsicum* spp.) in Thailand. *Plant Pathology*. 2008;57(3):562-572.
23. Thind TS, Jhooty JS. Relative prevalence of fungal diseases of chilli fruits in Punjab. *Indian Phytopathology*. 1985;38:305-307.
24. Wheeler BE. An introduction to plant diseases. London: John Wiley and Sons Ltd.; 1969. p. 301.