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Review Article

Trichoderma spp. for the Sustainable Management of Northern Corn Leaf Blight: Biology, Mechanisms of Action, Practical Applications and Future Perspectives

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ABSTRACT

Exserohilum turcicum, the causal agent of northern corn leaf blight (NCLB), is one of the most destructive foliar pathogens of corn, causing significant yield losses and threatening global corn production. The increasing demand for sustainable disease management has stimulated interest in using *Trichoderma* spp. as biological control agents in integrated disease management (IDM) programmes. This review synthesises current knowledge on the potential of *Trichoderma* spp. for managing NCLB, with emphasis on their biology, mechanisms of action, practical application and future perspectives. Studies consistently demonstrated that *Trichoderma* spp., particularly *T. asperellum*, *T. harzianum*, and *T. virens*, effectively suppress *E. turcicum* under *in vitro*, greenhouse, and field conditions. Their biocontrol efficacy is attributed to multiple complementary mechanisms, including mycoparasitism, production of antifungal metabolites and cell wall-degrading enzymes, competition for nutrients and ecological niches, and activation of induced systemic resistance (ISR) in the host plant. The review also examines the integration of *Trichoderma* with fungicides and cultural practices, highlighting their compatibility and potential for synergistic effects. Furthermore, available formulation and delivery methods, including seed treatments, soil applications,

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seedling inoculation, and foliar sprays, are discussed with respect to their effectiveness under different production systems. Finally, key challenges, including inconsistent field performance, environmental influences, formulation stability, commercialisation constraints, and regulatory considerations, are critically evaluated. Addressing these knowledge gaps through multidisciplinary research will facilitate the wider adoption of *Trichoderma*-based biocontrol strategies as sustainable components of IDM programmes to effectively manage northern corn leaf blight.

Keywords: Antagonism, antibiosis, biological control, *Exserohilum turcicum,* northern corn leaf blight, *Trichoderma*

INTRODUCTION

Corn (*Zea mays* L.) is one of the most important cereal crops and a key member of the Poaceae family. It is a staple food for millions of people and the raw material for livestock feed and many industrial products such as starch, glucose, ethanol, cooking oil, paper, cosmetics, and pharmaceuticals (Reddy, 2008). Corn is economically and nutritionally important, and stable corn productivity is needed for sustainable global food security.

Despite ongoing improvements in crop production, corn is still plagued by several diseases that reduce yield and grain quality. Northern corn leaf blight (NCLB), also known as *Turcicum* leaf blight, is one of the most damaging foliar diseases in corn production, especially in warm and humid areas of the world (Ijaz & Fan, 2024). The disease is caused by *Exserohilum turcicum* (syn. *Setosphaeria turcica*) and may result in yield loss ranging from 15-66%, depending on the cultivar, the environment, and the stage of crop development at infection (Manu et al., 2018). NCLB is characterised by long elliptical, greyish-green to tan necrotic lesions on the leaves and progressively decreases the area around the photosynthetic plant cells. Infection during the tasselling and grain-filling stages can significantly reduce kernel production and grain yield, especially during prolonged periods of high humidity and moderate temperatures, which support pathogen growth.

Chemical fungicides remain an important and commonly used approach to managing NCLB because they are fast and effective at disease control and easily available to growers. However, repeated fungicide use increases the cost of production and has environmental implications for fungicide residues and the development of fungicide-resistant pathogen populations. These challenges have motivated the search for sustainable and environmentally friendly solutions for integrated disease management (IDM) programmes.

Trichoderma species are among the most promising biological control agents, attracting considerable attention for their diverse antagonistic activity against many plant pathogens. *T. harzianum, T. asperellum,* and *T. virens* have been shown to suppress soil-borne or foliar pathogens in different ways, such as mycoparasitism, competition for nutrients and space,

secretion of antifungal metabolites and cell wall-degrading enzymes and induced systemic resistance (ISR) in host plants. Moreover, *Trichoderma* is compatible with other disease management strategies, including fungicide application, crop rotation, and the cultivation of resistant corn hybrids, and is an ideal component in IDM programmes.

Environmental concerns, stricter pesticide regulations, and the growing prevalence of fungicide resistance have stimulated interest within the biotech community in biologically based crop protection measures. Although *Trichoderma* is excellent at combating soil-borne pathogens, its use in controlling foliar diseases such as northern corn leaf blight has gained momentum in recent years. *Trichoderma* can directly antagonise *E. turcicum* and enhance the plant's innate defense responses, thereby reducing disease severity under greenhouse and field conditions. Research into the biological control mechanisms of *Trichoderma* spp., particularly mycoparasitism, antibiosis, and induced systemic resistance, represents a novel and significant approach to developing effective field-level management strategies against *E. turcicum*. This research addresses the persistent gap between mechanistic laboratory studies and their practical translation into sustainable, long-term disease management strategies for NCLB.

This review summarises the current state of knowledge about *Trichoderma*-based management of NCLB. We discussed the biology and epidemiology of *E. turcicum,* the mechanisms of *Trichoderma*-mediated disease suppression, and practical applications; then we presented the current challenges and the research gaps that are open for the implementation of *Trichoderma*-based biocontrol for sustainable corn production.

LITERATURE SEARCH METHODOLOGY

To ensure systematic and comprehensive coverage of the available literature, relevant papers were extracted from major scientific databases, such as Web of Science, Scopus, PubMed, and Google Scholar. A combination of terms like "*Trichoderma*," "biocontrol," "Northern Corn Leaf Blight," "*Exserohilum turcicum*," "*Setosphaeria turcica,"* "mechanisms of action," "mycoparasitism," "induced systemic resistance," and "sustainable disease management" was used in the search.

Publications from January 2005 to 2025 were included in the search, which captured both early and current developments in the subject. Peer-reviewed original research publications, review papers, and book chapters published in English that particularly discussed *Trichoderma*-mediated biocontrol mechanisms, its use against foliar pathogens, or NCLB management techniques were among the inclusion criteria. Figure 1. Articles unrelated to *Trichoderma*-pathogen interactions, non-peer-reviewed sources, conference abstracts without complete data, and studies without experimental validation were all disregarded. Before the final screening and synthesis, duplicate records across databases were removed.

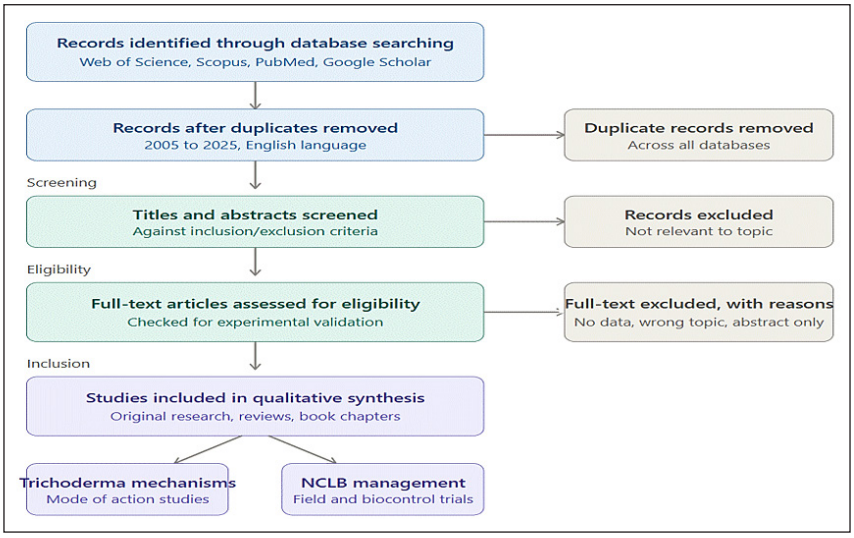


Figure 1. PRISMA flow diagram of the literature search strategy

BIOLOGY AND EPIDEMIOLOGY

Biology

E. turcicum is the anamorphic (asexual) stage of the NCLB pathogen, and *S. turcica* is the teleomorphic (sexual) stage. *E. turcicum* and *S. turcica* are two names for the same species of fungus that were previously described using a dual nomenclature system: *S. turcica* indicates the sexual (teleomorphic/ascosporic) state of this pleomorphic fungus, while *E. turcicum* indicates the asexual (anamorphic/conidial) state. This pathogen is best known for causing NCLB, also known as turcicum leaf blight in corn. It also causes a similar leaf blight in sorghum and other grasses. However, the study of fungal systematics and molecular phylogenetics has led to several taxonomic changes. *E. turcicum* is now placed in the Ascomycota phylum, Dothideomycetes class, order Pleosporales, and family Pleosporaceae. NCLB is a hemibiotrophic fungal pathogen that first begins a biotrophic relationship with the host before progressing to a necrotrophic phase. *E. turcicum* first colonises living host tissue before transitioning to a necrotrophic phase and causing tissue necrosis. The biotrophic phase lasts for about eight days before the fungus transitions to necrotrophy (Human et al., 2020). Under favourable conditions, especially at moderate temperatures (18-28 °C) and with wet leaves, the pathogen produces large conidia on infected leaf tissue. These airborne conidia are easily dispersed by wind and rain splash and can lead to secondary infections of healthy corn leaves and rapid disease spread in and between fields. Host resistance is still an important part of NCLB management.

Although resistant cultivars can be a good way of disease suppression, their durability is limited, and host resistance should be incorporated into other management strategies as part of the IDM programme (Ali et al., 2024).

The pathogen produces conidia that are fusiform to obclavate; although they can also appear ellipsoidal, spindle-shaped, cylindrical, elongated, straight, or slightly curved (Abebe & Singburaudom, 2006). The mature conidia are 52.94-144.12 µm in length and have a distinctive protruding hilum, which is the main characteristic of the genus *Exserohilum* (Anwer et al., 2022). The conidia are pale brown to dark brown, multicellular, and have 1-9 septa, with septation becoming more pronounced as the conidia grow. The conidiophores are solitary and arranged in small groups, and are 47-443 × 4-6 µm in length, cylindrical, septate, flexuous, geniculate, and olivaceous brown in color, with conidia produced terminally at their apices (Anwer et al., 2022). Colony morphology in culture varies with the isolate, culture medium, nutrient composition, and pH. Colonies are usually olivaceous brown, dark brown, grayish brown, or whitish black, reflecting the phenotypic variation among *E. turcicum* isolates under different growth conditions (Anwer et al., 2022).

Disease Development

NCLB disease cycle is shown in Figure 2. The inoculum (conidia) will germinate and develop a germ tube after it lands on the host. Germination is bipolar, and the incubation period is usually 12-24 hours (Ali & Chowdhury, 2014). The infection peg is initiated when the conditions are suitable (Muiru et al., 2008). Once the infection peg has made it through the stomata or cell wall successfully, it colonises both intracellular and intercellular spaces. As a consequence, the pathogen kills the surrounding cells at the site of infection (Ali & Chowdhury, 2014). Conidiophores are usually produced in clusters from the adaxial and abaxial stomata, while single conidia form at the end of the conidiophore, which appears to be dark (Anwer et al., 2022). As a result, symptoms were noted, including small dark spots on the lower leaves that eventually grew into larger ones that ultimately blighted whole leaves (Ali & Chowdhury, 2014). When conditions are unfavourable, *E. turcicum* grows in crop remnants that have not decomposed after harvest.

Infected leaves usually exhibit small, slightly oval, water-soaked symptoms that start on lower leaves and move upwards if no disease control is applied (Agrios, 2005; Ali & Chowdhury, 2014). In severe cases, these tiny spots will grow and unite to form blight symptoms on the entire leaf (Harlapur et al., 2008) and affect the photosynthesis process (Pooja et al., 2023; Swathi et al., 2021). The length of the lesion varies from 2.0 to 15.5 cm, and the width varies from 0.5 to 2.0 cm (Ali & Chowdhury, 2014).

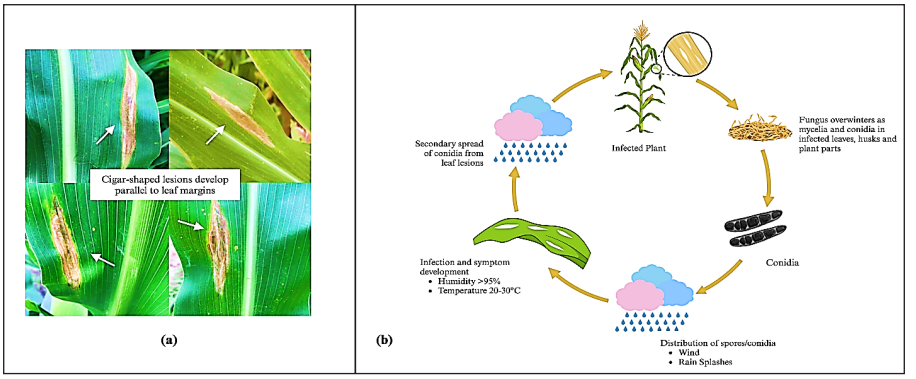


Figure 2. (a) Symptoms of northern corn leaf blight (NCLB) on corn leaves and (b) life cycle of NCLB disease. During overwintering, the use of NCLB as an alternate host on corn leaves leaves conidia and mycelia on the soil surface. However, under warm, humid conditions, infected corn debris produces new conidia, which are the main source of inoculum. Afterward, the NCLB spreads by rain and wind to distant areas and falls on the leaf surface
Source: Adapted and modified (Ijaz & Fan, 2024)

Disease Severity and Yield Loss

The severity of northern corn leaf blight (NCLB) is strongly dependent on the environment (temperature, relative humidity, leaf wetness, rainfall, and altitude (Abebe & Singburaudom, 2006). Good environmental conditions lead to disease development and can cause a significant decline in corn productivity. The reported yield loss due to NCLB ranges from 15% to 66%, depending on disease severity, cultivar susceptibility, and the current environment (Manu et al., 2018). The yield loss is also affected by corn genotype, crop growth stage at the time of infection, pathogen virulence, and environmental conditions. The timing of infection is one of the most important factors in economic damage. Early infection, especially prior to or during tasseling and silking, results in severe damage to the photosynthetically active leaf tissue, and grain filling is severely affected. Infections in the later stages of crop development have a smaller impact on grain yield, as most kernel development has been completed by then. Previous studies have reported that yield losses can be from 28-91% when the disease starts before or around silking, and if it starts 6-8 weeks after silking, yield loss is very low (Swathi et al., 2021).

Weather Factors Influencing Disease Severity

The severity and transmission of disease are influenced by temperature, humidity, rainfall, and wind (Saeed et al., 2023). The number of consecutive wet days, rainfall, relative humidity, and pathogen spore production are positively correlated with climatic conditions (Indira & Muthusubramanian, 2004). As such, Northern corn leaf blight thrives in warm, humid conditions. The highest disease prevalence is observed between 25-30 °C, with

humidity between 75-90% (Saeed et al., 2023). In addition to temperature and the date of sowing, other factors affect disease severity. The disease is more severe at lower elevations than at higher elevations (Abebe & Singburaudom, 2006). The planting date also affects disease severity. Postponing the sowing date is more serious because humidity and temperature are usually higher at lower elevations (Ali et al., 2014). The highest disease severity was found in Karnataka, India, when corn was planted in the September season (Harlapur et al., 2007).

MECHANISMS OF ACTION

The mechanisms of action of *Trichoderma* spp. that reduce foliar and root diseases fall into two broad categories: direct and indirect antagonism. *Trichoderma* is responsible for controlling corn leaf blight mainly through direct antagonism of the pathogen and rapid colonisation of plant tissues before the pathogen forms (Manzar et al., 2024; Yao et al., 2023). In maize, this means rapid growth and competition for space and nutrients, the secretion of antifungal metabolites, and the production of cell wall-degrading enzymes that weaken the blight pathogen (Yao et al., 2023).

A direct mechanism is mycoparasitism. *Trichoderma* attaches to the pathogen hyphae, coils around them, and enters the fungal cell wall. It then releases chitinases, glucanases, proteases, and other lytic enzymes that destroy the pathogen's structure, causing hyphal deformation, lysis, and lack of spore germination (Yao et al., 2023). *Trichoderma* produces volatile and non-volatile secondary metabolites that suppress pathogen growth, slow mycelial expansion, and limit lesion development in corn leaves. Recent studies on corn also show that effective *Trichoderma* strains reduce leaf blight severity and increase defensive enzymes and lignification, thereby conferring stronger resistance to infection (Manzar et al., 2024). In practice, these direct actions reduce pathogen pressure on the leaf surface and in infected tissue, which helps to control blight progression and yield loss (Yao et al., 2023). So, for corn leaf blight, *Trichoderma* is not only a competitor but also a fungal parasite and chemical antagonist to the pathogen (Manzar et al., 2024; Yao et al., 2023). These are particularly effective when these functions are applied in controlled experiments and in contact with fungal pathogens, such as on organic residues, the phyllosphere, and as foliar treatments (Harman, 2006).

Indirect antagonism of *Trichoderma* against corn leaf blight refers to disease suppression through plant-mediated defense rather than only direct contact with the pathogen. In corn, *Trichoderma* colonise s the rhizosphere or root surface and triggers induced systemic resistance, so the plant responds faster and more strongly when leaf blight pathogens attack. For the case of *T. virens* and *P. chlororaphis,* even in the absence of the inoculum on the leaf surface, this priming can lessen the severity of foliar diseases by inducing host resistance. Studies have shown that certain *Trichoderma* strains that interact with roots can initiate induced systemic resistance (ISR), which inhibits the growth of foliage pathogens

(Saravanakumar et al., 2017). This indirect action works mainly through activation of defense enzymes and signalling pathways. There is indirect evidence that, in fodder corn infected with *Bipolaris maydis*, *Trichoderma* treatment increased peroxidase, superoxide dismutase, and catalase activities, which are linked to stronger antioxidant defense and reduced disease severity. The study also noted that *Trichoderma* can stimulate plant defenses through secondary metabolites and other elicitors, supporting systemic resistance against fungal pathogens. Studies have shown that when *Trichoderma* is applied to roots or seeds, it induces ISR, and this reaction is very useful for reducing the severity of foliar diseases (Saravanakumar et al., 2017).

A study showed that *Trichoderma* can rapidly adsorb to the roots of crops for growth, and the hyphae can quickly wrap around the roots of crops to form a protective layer that protects the roots from the invasion of phytopathogens and kills nearby pathogens (Resoli et al., 2022). Some indirect evidence revealed that the growth rate of *T. harzianum* was 2-4.2 times faster than that of *Botrytis cinerea* (Dugassa et al., 2021). Given this nature, T. *harzianum* could easily overcome the pathogen. Herrera-Téllez et al. (2019) found that *Trichoderma* could compete with *Fusarium graminearum* by clinging, twining, interpenetration, and other mechanisms, in which the mycelia of *F. graminearum* were deformed and disappeared. *Trichoderma* can take up water and nutrients, occupy space, and consume oxygen through rapid growth and reproduction, thereby weakening and excluding grey mold pathogens in the same habitat (Herrera-Téllez et al., 2019). A schematic diagram of the mechanism of action of *Trichoderma* spp. against plant fungal diseases is shown in Figure 3.

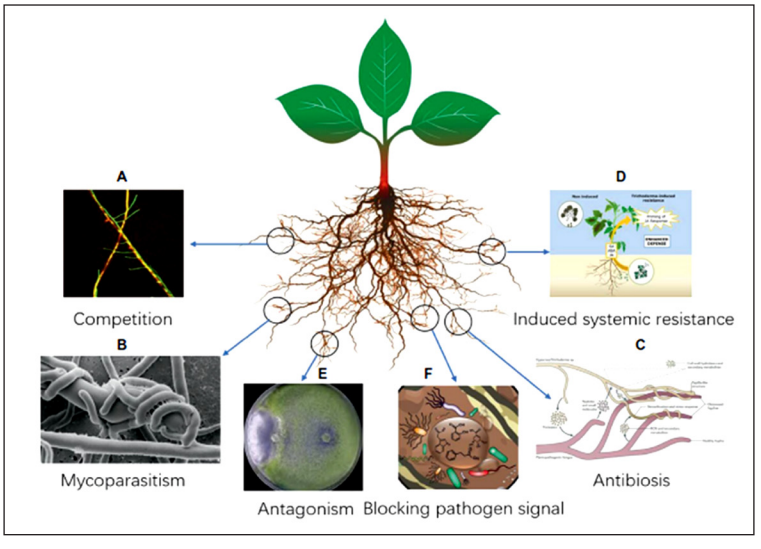


Figure 3. Schematic representation illustrating the mechanisms by which *Trichoderma* exerts biocontrol activity within plant- pathogen interactions
Source: Adapted and modified (Yao et al., 2023)

DISEASE MANAGEMENT

Trichoderma is found everywhere and has great promise and application potential (Tyśkiewicz et al., 2022). It is a filamentous fungus that grows rapidly in tropical soils and plant rhizospheres. *T. harzianum, T. viride, T. asperellum, T. atroviride,* and *T. longibiatum* are the most common species studied and used for biocontrol purposes. *Trichoderma* isolates are used for seed treatments, soil amendments, foliar applications, and as endophytes. They can be formulated as powders, wettable powders, granules, liquid broths, and cell-free filtrates. Some of the features of *Trichoderma spp*. include rapid saprophytic growth (competition), hydrolytic enzymes, secondary metabolite production, the ability to parasitise phytopathogens, plant systemic resistance, growth promotion, and compatibility with fungicides and agricultural practices (Oyesola et al., 2024). Many bacterial and fungal bioagents have been widely used, alone or in combination, for the control of NCLB (Sartori et al., 2017). *Trichoderma spp*. could grow far faster than fungal pathogens (Mohiddin et al., 2021). *Trichoderma* also exhibits several disease-control processes, including parasitism, antagonism, nutrient competition, and the production of substances harmful to pathogens (El-Baky & Amara, 2021). Among them, *T. viride* (Kumari et al., 2020; Subedi et al., 2019), *T. harzianum* (Rani et al., 2022), *T. asperellum* (Limdoltham et al., 2023; Ma et al., 2023), *T. hamatum*, and *T. harzianum* (Limdoltham et al., 2023) are the most likely candidates for the biological components of the IDM programme.

Trichoderma's diverse roles as biocontrol agents, growth promoters, and modulators of the plant microbiome are highlighted by literature reviews and meta-analytical investigations (Harman, 2006). Several studies have reported a significant reduction in NCLB severity and improvement in corn yield. The efficacy of the *Trichoderma* formulations was evaluated through seed treatment, soil application, and foliar spraying (Table 1).

Variations in control efficacy likely reflect strain-specific characteristics and differences in the mechanisms employed. Single-species applications of *T. viride* and *T. asperellum* may rely predominantly on antibiosis and competitive exclusion, resulting in moderate disease suppression (35-55%). In contrast, *T. harzianum* and *Trichoderma* consortium treatments achieved higher disease reduction (45-65%), potentially reflecting the complementary or synergistic effects of mycoparasitism, antibiosis, competition, and induced systemic resistance (ISR). Seed treatment may also provide greater and more consistent protection than foliar application because early establishment of *Trichoderma* in the rhizosphere can facilitate root colonisation and activate ISR before pathogen infection occurs. In comparison, foliar-applied *Trichoderma* is primarily restricted to the treated tissues and may be more vulnerable to environmental factors such as rainfall and UV exposure, which can reduce persistence and colonisation.

Table 1
Efficacy of Trichoderma *spp. and comparative treatments against* Exserohilum turcicum *in corn*

Treatment	Formulation	Mode of Application	Experimental Conditions	Disease Reduction (%)	Observed Effects	Limitations	References
Trichoderma Harzianum (strains T-22, T-1295)	Talc-based powder/conidial suspension for seed coating	Seed treatment	Field and Greenhouse trials on maize; artificial inoculation with *E. turcicum*	45-60%	Reduced lesion size, improved seedling vigour	Efficacy varies with soil moisture/temperature; requires adequate propagule viability; limited persistence in field soils	Harman et al. (2004)
Trichoderma viride	Talc-based formulation / liquid soil drench	Soil application	Pot and field trials on maize seedlings challenged with *E. turcicum*	40-55%	Suppressed *E. turcicum*, enhanced root growth	Sensitive to soil pH and temperature fluctuations; inconsistent rhizosphere colonisation	Kumar & Reddy (2016)
Trichoderma asperellum	Conidial suspension for foliar spraying	Foliar spray	Greenhouse and field trials on maize	35-50%	Lower disease index, increased biomass	Reduced persistence under UV exposure/ rainfall; requires repeated applications	Vinale et al. (2008)
Trichoderma spp. (consortium)	Combined seed coating and soil-applied granules/ suspension	Seed + soil application	Multi-location field trials on maize	50-65%	Induced systemic resistance, higher yield	Higher cost and logistical complexity; strain compatibility must be verified	Mukherjee et al. (2013)
Chemical fungicide (check)	Emulsifiable concentrate / wettable powder	Foliar spray	Standard field trial practice on maize	60-70%	Effective disease control but residue risk	Chemical residues, environmental impact, risk of resistance development	Agrios (2005)
Untreated control	-	-	Same trial conditions, no treatment applied	0%	High disease severity and yield loss	Represents worst-case scenario; not a management option	Shaner & Stromberg (1981)

The discrepancy between greenhouse and field performance further highlights the importance of environmental and ecological factors. Under controlled greenhouse conditions, relatively stable humidity, temperature, and pathogen inoculum levels may favour *Trichoderma* establishment and exaggerate its apparent efficacy. Under field conditions, fluctuating temperature, rainfall, UV exposure, and competition with indigenous microorganisms can substantially reduce colonisation and biocontrol activity. Therefore, while antibiosis and direct competition may contribute substantially to disease suppression under controlled conditions, rhizosphere establishment, mycoparasitism, and particularly ISR are likely to become increasingly important for maintaining *Trichoderma* efficacy under variable and challenging field environments.

PRACTICAL APPLICATION

In-Vitro Studies

In-vitro studies are used to screen potential strains from soil and leaf microenvironments (Sartoria et al., 2015), while Khamari and Beura (2014) found that *T. viride* and *T. harzianum* showed strong suppression effects with percent growth inhibition rate values of 84.7% and 81.7%, respectively, against the tested phytopathogen.

Greenhouse Trial

Many *Trichoderma* species were tested using seed treatments, soil drenches, root inoculations, and foliar sprays in greenhouse and growth-chamber experiments. Studies have shown that seedlings treated with *Trichoderma* have higher growth and biomass and fewer disease lesions (e.g., after artificial inoculation with E. *turcicum*). Seed treatments with *T. harzianum* reduced pathogen colonisation in seedlings, and pot experiments with *T. asperellum* showed it protected them from *E. turcicum.* These data support the notion that induced systemic resistance (ISR) is in concert with direct hostile activity (Ma et al., 2023).

Field Trials

Field experiments of *Trichoderma* for NCLB disease control produced mixed but encouraging results. *T. asperellum* strain 576 significantly reduced *E. turcicum* disease infections and promoted corn seedling growth under field settings. Similarly, the wet formulation of endophytic *Trichoderma* was shown to successfully control NCLB compared with the dry formulation, and it is clear that both formulation and viability are important factors in field applications (Ma et al., 2023). Wang et al. (2025) reported a 72% decrease in NCLB disease incidence after treatment with *Trichoderma* in combination with difenoconazole (low rate); therefore, the fungicide treatment strategy should be effective and can be integrated with *Trichoderma* to reduce chemical dosage and increase control efficacy.

However, the fungicide tolerance and compatibility of the specific strain of *Trichoderma* used is important (Wang et al., 2025). Ma et al. (2023) conducted a comprehensive field study that showed corn seedlings injected with or treated with both *E. turcicum* 101 and *T. asperellum* 576 showed major improvement after being treated with a 10^7-spores/mL conidial suspension using foliar spraying and soil drenching. This indicates that *T. asperellum* 576 is a very promising strain. It has the potential to be an effective biocontrol agent in the control of diseases, as it acts as an inhibitor of the production of inhibitory chemicals and stimulates plant growth. Table 2 summarises the field disease control efficacy of NCLB. Biological antagonists, such as *Trichoderma*, reduce the incidence of corn diseases in a variety of agricultural studies. However, the differences in performance are largely due to local climate variations, fungal strain variations, product formulation, and application timing (Limdolthamand et al., 2023; Subedi et al., 2019). Moreover, control efficacy varies considerably among studies because of differences in *Trichoderma* strains, pathogen isolates, inoculum density, and application methods, including seed, foliar, and soil applications, making direct comparisons difficult. Environmental factors such as temperature, relative humidity, soil pH, and competition within the rhizosphere can further influence *Trichoderma* colonisation, establishment, and antagonistic activity, potentially explaining differences in performance across locations. Among the evaluated species, *T. harzianum* and *T. asperellum* appear to show relatively consistent biocontrol potential, possibly due to their ability to employ multiple complementary mechanisms, including mycoparasitism, hydrolytic enzyme production, antibiosis, competition, and induction of plant defence responses. However, reproducibility across studies remains limited because of non-standardised bioassays, differences in experimental conditions, insufficient field validation, and the frequent reliance on laboratory-based inhibition assays. Therefore, claims regarding the comparative superiority of particular *Trichoderma* strains or species should be interpreted cautiously, and robust conclusions require standardised methodologies and replicated multi-location, multi-environment field trials under realistic disease and environmental conditions.

FORMULATION AND DELIVERY OF *TRICHODERMA*

Seed Treatment

Trichoderma spores are very practical to use as a seed coating. Early root colonisation and ISR can be achieved in the early stages of plant growth, which is also simpler and relatively inexpensive. This kind of seed treatment has been shown to be effective against a variety of corn diseases and is widely used to control early-season diseases and seedborne pathogens. However, seed coating always requires fresh, viable spores and can be integrated with other seed treatments, such as insecticides or fungicides (Mastouri et al., 2010).

Table 2
Field application of single and consortia of Trichoderma *spp. for controlling corn disease*

Treatment	Strain Origin	Formulation	Mode of Application	Experimental Conditions	Observed Effects	Limitations	References
Trichoderma harzianum	Soil-derived rhizosphere isolate (maize rhizosphere)	Talc-based powder seed coating (1×10^8 cfu/g)	Seed treatment	Greenhouse pot trial + multi-location field trial, maize, natural + artificial inoculation with *E. turcicum*	Reduced lesion size, improved seedling vigour	Efficacy varies with soil temperature/ moisture; needs viable seed coat contact	Harman et al. (2004)
Trichoderma Viride	Rhizosphere soil isolate	Liquid spore suspension (1×10^7 spores/mL)	Soil application	Field trial, maize, natural epiphytotic conditions	Suppressed *E. turcicum*, enhanced root growth	Slower onset of protection; repeat application often required	Kumar & Reddy (2016)
Trichoderma asperellum	Endophytic/ rhizosphere isolate	Aqueous spore suspension (foliar grade)	Foliar spray	Greenhouse + field trial, maize	Lower disease index, increased biomass	Spore viability reduced by UV exposure and low leaf-surface humidity	Vinale et al. (2008)
Trichoderma spp. (consortium)	Multi-strain synergistic combination	Combined talc (seed) + liquid (soil) formulation	Seed + soil application	Multi-season field trials, maize	Induced systemic resistance, higher yield	Strain compatibility/ shelf-life challenges; higher production cost	Mukherjee et al. (2013)
Chemical fungicide (check)	synthetic compound	Emulsifiable concentrate / wettable powder	Foliar spray	Field trial, corn, standard agronomic practice	Effective disease control but residue risk	Chemical residues, non-target/ environmental toxicity, resistance risk	Agrios (2005)
Untreated control	-	-	-	Same trial conditions, no treatment applied	High disease severity and yield loss	Not applicable (reference treatment)	Shaner & Stromberg (1981)

Soil Amendments and Foliar Spray

Soil drench is widely used in greenhouse studies, and this method achieves high-scale root colonisation and disease control efficacy. However, granular and liquid formulations are commonly used under field settings and adopted during planting or in-furrow systems. In foliar spray treatment, *Trichoderma* spores are inoculated directly onto the corn leaf surface to produce antifungal chemicals or to prevent *E. turcicum* spores from germinating. Protective formulations, in addition to adhesion agents, were applied during late evening to improve the survival rate of *Trichoderma* strains on the leaf surface. This practice significantly increases the likelihood of successful outcomes, given that the phyllosphere is a challenging environment (e.g., UV radiation, moisture loss). Foliar treatments have been shown to reduce the spread of disease lesions in field experiments. However, persistence on the leaf surface is generally lower than in soil-root systems and is therefore more susceptible to repeated applications (Limdolthamand et al., 2023).

Wet and Dry Formulations

Fresh or wet formulations (e.g., wettable powders and liquid fermentation) can be more effective in the field than dry formulations. Dry formulations (such as powders and granules) have logistical advantages in terms of storage and transportation. However, spore viability, proper drying procedures, and carrier selection are required. According to sweet corn field testing, fresh formulations inhibited northern corn leaf blight (NCLB) more successfully than dry powders did for some strains (Limdolthamand et al., 2023).

INTEGRATED DISEASE MANAGEMENT

Compatibility with Host Resistance

Trichoderma provides a multi-faceted defense strategy in NCLB disease control. It can be incorporated with host resistance via gene pyramiding and quantitative resistance to avoid reliance on individual resistance genes. This is because the plant will respond, to a lesser extent, to specific major-gene resistance pathways and to *Trichoderma* ISR, which can enhance the host's genetic defense capability. Field tactics should emphasise resistant hybrids in combination with *Trichoderma* (Ali et al., 2024).

Compatibility with Fungicides

Fungicides are commonly used in the NCLB disease management programme. While some fungicides are proven compatible with *Trichoderma* spp., others can inhibit the growth of these beneficial fungi. There has been evidence that *Trichoderma* application can lower the dosage of synthetic fungicides (difenoconazole) and lead to additive or complementary effects in NCLB disease control. This strategy reduces the use of fungicides while still providing effective disease control. Before using combined treatments, compatibility testing

should be conducted in controlled laboratory settings or under field conditions. The other important factor is the timing of application (Wang et al., 2025).

Cultural Practices and Residue Management

Effective residue management, such as tillage, residue removal, and rapid decomposition, can reduce the amount of pathogen inoculum and increase the effectiveness of biological control measures since *E. turcicum* inoculum remains on crop residues after the harvesting stage. Interestingly, applying *Trichoderma* to corn residues not only accelerates decomposition but also reduces the pathogen's survival rate. However, the effectiveness of residue management systems that favour *Trichoderma* colonisation may vary with climatic conditions and specific cropping systems. Thus, it is logical to integrate residue management strategies with *Trichoderma* applications from an epidemiological perspective (Wang et al., 2025).

Response/Addition Regarding PR Genes and R Genes

The activation of plant innate immune pathways, particularly through the upregulation of pathogenesis-related (PR) genes and modulation of resistance (R) gene-mediated defence, is closely associated with *Trichoderma*-mediated resistance in maize against NCLB caused by *E. turcicum*. Following root or foliar colonisation, *Trichoderma* spp. can induce systemic resistance (ISR), leading to enhanced expression of defence-related genes, including *PR-1*, *PR-2* (β-1,3-glucanase), *PR-3* (chitinase), and *PR-5* (thaumatin-like proteins). The products of these genes contribute to cell-wall reinforcement and the inhibition of pathogen growth. In addition, R genes encoding nucleotide-binding site- leucine-rich repeat (NBS-LRR) proteins play important roles in pathogen recognition and activation of downstream defence responses. *Trichoderma* colonisation may prime these defence pathways, enabling maize plants to mount a faster and stronger response following *E. turcicum* infection. This molecular perspective complements the direct biocontrol mechanisms discussed earlier and provides a more comprehensive understanding of how *Trichoderma*-mediated ISR may contribute to the suppression of NCLB.

LIMITATIONS AND KNOWLEDGE GAPS

Variable Field Efficacy

The main limitation is that performance varies from field to field. Extreme temperatures, ultraviolet radiation, drought conditions, soil and leaf microbiomes, and agricultural practices were major factors affecting the establishment and long-term survival of *Trichoderma* spp. To assess reliability and identify resilient strains suited to various agroecological conditions, the experiments should be conducted across multiple locations and over multiple years (Limdolthamand et al., 2023). The effectiveness of *Trichoderma* in controlling the NCLB of corn is summarised in Table 3.

Table 3
Research gaps regarding the effectiveness of Trichoderma *spp. in controlling the NCBL of corn*

Research Gap	Description of Gap	Causes	Remark & References
Limited field-level efficacy data for *Trichoderma* against NCLB	Most studies are conducted under *greenhouse or lab conditions*; robust multi-location field trials across diverse environments are scarce.	Field factors (climate, soil microbes) can significantly alter biocontrol performance compared to controlled conditions.	Endophytic *Trichoderma* spp. tested in initial field trials, but broader validation is still needed (Limdolthamand et al., 2023)
Comparative performance of different *Trichoderma* strains	Few comparative studies evaluate multiple *Trichoderma* species or isolates for antagonism against *E. turcicum*	Identifying the most effective strains is essential for reliable biocontrol product development.	*T. asperellum* 576 shown to suppress *E. turcicum* but other isolates less characterised (Ma et al., 2023)
Mechanistic understanding of biocontrol action	Underlying modes of action (e.g., systemic induced resistance vs antibiosis vs competition) of *Trichoderma* on NCLB interaction is poorly resolved.	Understanding mechanisms helps optimise formulation and predict efficacy under stress.	While antagonism is reported, detailed host- biocontrol mechanisms are not fully elucidated (Ma et al., 2023)
Integration with existing disease management practices	Few studies explore interactions between *Trichoderma* applications and fungicides or other cultural practices in NCLB control.	Synergistic or antagonistic effects with agrochemicals need evaluation for integrated pest management (IPM).	Combined *Trichoderma*-fungicide treatments show promise, but comprehensive analysis is limited (Wang et al., 2025).
Long-term effects on corn yield and soil microbiome	Long-term impacts of repeated *Trichoderma* application on yield stability and soil microbial communities remain largely unexplored.	Sustainable use requires understanding soil ecology and crop performance over seasons.	Most studies focus on short-term disease suppression rather than multi-season outcomes. (Inferred from lack of longitudinal data)
Effectiveness under varying environmental conditions	The efficacy of *Trichoderma* across environments (e.g., humidity, temperature gradients) is underreported.	NCLB severity and biocontrol performance is both highly influenced by environmental conditions.	Existing field data limited to specific regions; broader climatic range missing (Limdolthamand et al., 2023)
Standardisation of formulations and application methods	There is a lack of standardised protocols for formulations (fresh vs dry), dosages, and application timing for NCLB control.	Standard protocols are needed for reproducibility and commercialisation.	Fresh formulations showed better effects than dry in one study (Limdolthamand et al., 2023)
Host plant responses (molecular and physiological)	Limited insights into how maize defense pathways are *activated or modified* by *Trichoderma* in the context of NCLB.	Molecular markers could serve as indicators of effective biocontrol and selection tools.	Mechanistic studies for other diseases (e.g., SCLB) exist, but NCLB-specific host responses are less studied (Lang et al., 2025)

Interactions with Synthetic Fungicides

Some fungicides and pesticides can suppress *Trichoderma* activity. There is ongoing research on finding compatible chemical formulations with appropriate tank-mix combinations and the best application sequence, whether to apply *Trichoderma* before or after fungicide treatment. A comprehensive study to uncover differences in fungicide tolerance between different strains indicates that compatibility testing is required for each strain (Korkom & Ünal, 2025).

Standardisation of Trials

Introducing standard protocols for strain assessment, formulation evaluation, and field trial reporting should accelerate progress in this field. Experimental designs, inoculation methods, and disease assessment techniques vary across studies. Establishing standard operating practices for these areas would advance disease control programmes (Sartoria et al., 2015).

FUTURE PERSPECTIVE AND CONCLUSION

Future research should investigate the interactions between different *Trichoderma* strains to identify complementary mechanisms of action and improve environmental resilience (Sartori et al., 2017). Comprehensive evaluations of the compatibility between fungicides and beneficial *Trichoderma* strains are also essential for developing integrated disease management strategies that reduce chemical inputs while maintaining effective disease control (Wang et al., 2025). To improve the effectiveness of biocontrol, future studies on *Trichoderma* spp. in controlling NCLB should combine omics-driven strategies with cutting-edge biotechnology. While metabolomics aids in the discovery of novel secondary metabolites with antifungal potential against *E. turcicum*, genomics and transcriptomics can identify antagonistic gene clusters and expression patterns triggered during pathogen-host interaction.

To improve disease suppression and plant resistance, microbiome engineering offers an opportunity to create synthetic consortia that combine *Trichoderma* with beneficial rhizobacteria. Precise strain improvement by CRISPR-based gene editing may increase mycoparasitism, induced systemic resistance, and stress tolerance features. Field effectiveness and commercial feasibility will be enhanced by developments in bioformulation technologies, such as nanoencapsulation, nanocarriers and shelf-stable spore formulations. AI-assisted strain selection can speed up the identification of better biocontrol candidates by screening genomic and phenotypic data using machine learning. Including these developments within a precision agriculture framework, such as remote sensing and site-specific application, will optimise *Trichoderma* deployment, ensuring targeted,

sustainable, and climate-resilient management of NCLB in corn production systems worldwide. In addition, molecular biomarkers and biochemical indicators that predict corn responses to ISR should be identified to improve the selection and monitoring of effective treatments. Greenhouse experiments should be validated using field-based data to ensure practical applicability under commercial farming conditions (Saravanakumar et al., 2017). Finally, participatory on-farm trials involving farmers, together with economic assessments of adoption barriers, supply chain logistics, and market acceptance of *Trichoderma*-based products, are necessary to support large-scale implementation (Sartori et al., 2017).

In conclusion, the synergistic effects of *Trichoderma* treatments in corn production systems are scientifically supported and represent an environmentally sustainable approach for managing NCLB. *Trichoderma* effectively suppresses disease through direct antagonism, antibiosis, and ISR, thereby reducing disease severity, enhancing host resistance, and lowering dependence on chemical fungicides. Although laboratory, greenhouse, and field studies have demonstrated promising results, successful field implementation depends on appropriate strain selection, effective formulation, suitable application methods, and favourable environmental conditions. Therefore, an integrated management strategy that combines well-adapted *Trichoderma* strains, optimised formulations, compatibility with fungicides and agronomic practices, and incorporation into comprehensive disease management programmes is recommended. Continued research, together with close collaboration among researchers, extension services, and farmers, will be essential to maximise the potential of *Trichoderma* as a sustainable and scalable solution for the management of northern corn leaf blight.

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